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ON THE

Strength, Elasticity, Ductility, and Resilience

OF

MATERIALS OF MACHINE CONSTRUCTION.

By PROF. R. H. THURSTON,

STEVENS INSTITUTE OF TECHNOLOGY,

HOBOKEN, N. J.

READ BEFORE THE

AMERICAN SOCIETY OF CIVIL ENGINEERS, NEW YORK.

PHILADELPHIA:
MERRIHEW & SON, PRINTERS, 135 NORTH THIRD STREET.
1874.

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HENRY MORTON,
Hoboken, N. J.

[From the Journal of the Franklin Institute, April, 1874.]

ON THE STRENGTH, ELASTICITY, DUCTILITY AND RESILIENCE OF MATERIALS OF MACHINE CONSTRUCTION,

And on Various Hitherto Unobserved Phenomena, Noticed during Experimental Researches with a New Testing Machine, fitted with an Autographic Registry.

By Prof. R. H. Thurston.

Read before American Society of Civil Engineers, Feb. 4, 1874.

Section I.

1. Introductory.*—Some months ago, while engaged with the advanced classes of the Stevens Institute of Technology, in experimental investigations of the resistance of materials, it was found that coëfficients were given, by various authorities, which neither accorded fully with each other or with those then obtained.

The desirability of determining how far these differences were due to errors of observation, and how far to variation in the quality of the materials examined, induced the writer to design several machines for the purpose of conducting with them a more extended and exact series of experiments. The machine for measuring torsional resistance was furnished with an automatic registry, recording a diagram which is a reliable and exact representation of all circumstances attending the distortion and fracture of the specimen. No system of personal observation could probably be devised which could yield results either as reliable or as precise as such a system of autographic registry, and, as no method previously in use had given simultaneously, and at every instant during the test, the intensity of the distorting force and the magnitude of the coincident distortion, it was anticipated that the new method of investigation might be fruitful of new and, possibly, important results. This expectation, as will be seen, has been more than realized.

* *Vide* Journal Franklin Institute.

2. Description of the Apparatus. —The machine, as planned by the writer, and as built in the instrument makers' workshop, at the Stevens' Institute, is shown in Fig. 1. This form is that with which the investigations to be described were made. Since its construction, in 1872, however, some changes and improvements have been made in the design to adapt it to general work, and new designs have been made for special kinds of work, as for wire mills, railroad shops and bridge building.

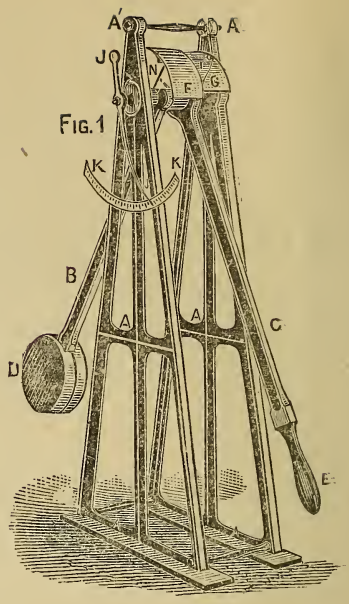


Fig. 1

Two strong wrenches, C E, B D, are carried by the frames A A, A^1 A^1, and depend from axes which are both in the same line, but are not connected with each other. The arm, B, of one of these wrenches carries a weight, D, at its lower end. The other arm, C, is designed to be moved by hand, in the smaller machines, and by a gear and pinion, or a worm gear in larger forms of the apparatus. The heads of the wrenches are made as shown in Fig. 2, the recess, M, being fitted to take the head, on the end of the test pieces, which is usually given the form shown in Fig. 4.

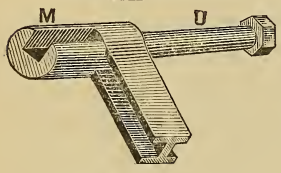


Fig. 2

Fig. 3

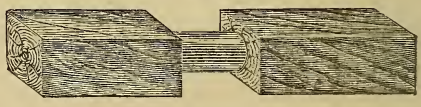


Fig. 4

A guide curve, F, of such form that its ordinates are precisely proportional to the torsional moments exerted by the weighted arm, B D, while moving up an arc, to which the corresponding abscissas of the curve are proportional, is secured to the frame A A^1. The pencil holder, J, is carried on this arm, B D, and as the latter is forced out of the vertical position, the pencil is pushed forward by the guide curve, its movement being thus made proportionate to the force which,

transmitted through the test piece, produces deflection of the weighted arm. This guide line is a curve of sines. The other arm, C E, carries the cylinder, G, upon which the paper receiving the record is clamped, and the pencil, J, makes its mark on the table thus provided. This table having a motion, relatively to the pencil, which is precisely the angular relative motion of the two extremities of the tested specimen, the curve described upon the paper is always of such form that the ordinate of any point measures the amount of the distorting force at a certain instant, while its abscissa measures the distortion produced at the same instant. The maximum hand, J, is sometimes useful as a check upon the record of maximum resistance.

The convenience of operation, the small cost,* and the portability of the machine are hardly less important to the engineer than the accuracy, and the extraordinary extent of information obtainable by it.

3. Method of Operation.—The test piece having been given the shape and size which are found best suited for the purpose of the experiment, and to the capacity of the machine, it is placed in the jaws of the two wrenches, each of which takes one of its squared ends, and, a force being applied to the handle, E, the strain thrown upon the specimen is transmitted through it to the weighted arm, B D, causing it to swing about its axis until the weight exerts a moment of resistance which equilibrates the applied force. As the magnitude of the distorting force changes, the position of the weight simultaneously changes, and the pencil indicates, at each instant, the value of the stress upon the test piece. As the piece yields under strains of increasing amount, also, the pencil is carried in the direction of the circumference of the cylinder on which its record is made and to a distance which is proportional to the amount of distortion, *i. e.*, to the "total angle of torsion." As the applied force increases, the specimen yields, and finally, rupture occurring, the pencil returns to the base line, at a distance from the starting point which measures the angle through which the test piece yielded before its fracture became complete.

4. Interpretation of the Diagrams.—It has been shown that the vertical scale of the diagrams produced is a scale of torsional moments, and that the horizontal scale is one of total angles of tor-

* Machines of the size of that used in these experiments, but of improved design, are made at the Stevens Institute, at prices as low as $150.

sion. Since the resistance to shearing, in a homogeneous material, varies with the resistance to longitudinal stress, it follows that the vertical scale is also, for such materials, a scale of direct resistance, and that, with approximately homogeneous substances, this scale is approximately accurate, where, as here, all specimens compared are of the same dimensions. Since the elasticity of the material is measured by the ratio of the distorting force, to the degree of temporary distortion produced, the diagrams obtained will exhibit the elastic properties of the material, as well as measure its ductility and its resilience.

Referring to the diagrams shown in the accompanying plates, it will be noticed that the first portion of the line is a curve of small radius, convex toward the axis of abscissas, and that the line then rises at a slight inclination from the vertical, but becoming very nearly straight, until, at a point some distance above the origin, it takes a reversed curvature. The first portion of the line is probably formed by the yielding of the loosely fitted packing pieces securing the heads of the specimen, and, after they have taken a bearing, by the early yielding, in some materials, of particles already overstrained. When a firm hold is obtained, the line becomes sometimes nearly straight, and the amount of distortion is seen to be approximately proportional to the distorting force, illustrating "Hooke's law," *Ut tensis sic vis.*

After a degree of distortion which is determined by the specific character of each piece, the line becomes curved, the change of form having a rate of increase which varies more rapidly than the applied force. When this change commences, it seems probable that the molecules, which, up to that point, retain generally their original distribution, while varying their relative distances, begin to change their positions with respect to each other, moving upon each other in a manner similar, probably, to that action described by Mon. Tresca, and called the "Flow of Solids,"* and to which attention has already been called by Prof. J. Thompson.†

It is this point, at which the line commences to become concave toward the base, that *is considered to mark the "limit of elasticity."* It will be noticed that it is well defined in experiments upon woods, is less marked, but still well defined in the "fibrous" irons and the less homogeneous specimens of other metals, and becomes quite indeterminable with the most homogeneous materials, as with the best

* L'Ecoulement des Corps Solides; Paris, 1869, 1871.

† Cambridge and Dublin Mathematical Journal, Vol. III, 1848, pp. 252—266.

qualities of well worked cast-steel. This point does not indicate the first "set," since, as will be hereafter seen, a set is found to occur, either temporary or permanent, and usually partly temporary and partly permanent, with every degree of distortion, however small. It is at this "elastic limit" that the set begins to become considerable in amount and almost wholly permanent.

The inclination of the straight portion of the line from the vertical measures the *stiffness* of the specimen, the quantity $Cot.\ \theta = \frac{1}{Tan.\ \theta}$ being the ratio of the distorting force to the amount of distortion up to the "limit of elasticity." As it would seem from the results of experiment, as well as of deduction, that this rigidity is very closely, if not precisely, proportional to the hardness, in homogeneous substances, this quantity $Cot.\ \theta$ may be taken, for practical purposes, as a measure of the hardness of the metals, as well as of their elastic resistance to compression.

After passing the elastic limit, the line becomes more and more nearly parallel to the base line, and then, with the woods invariably, and in some cases with the metals, begins to fall rapidly before fracture becomes evident in the specimen. Where the rising portion of the line turns and becomes nearly parallel with the axis of abscissas, the viscosity of the material is such that the outer particles "flow" upon those within, and, while themselves still offering maximum resistance, permit molecules nearer the axis to also resist with approximately maximum force. It seems probable that, with the more ductile substances, nearly all are brought up to a maximum in resistance before fracture occurs, and this circumstance will be seen hereafter to have an important influence in determining the resistance to rupture. The hardest and most brittle materials break, with a snap, before any such flow becomes perceivable, and before the line of the diagram commences to deviate, in the slightest degree, from the direction taken at the beginning, and before the approach to the elastic limit is indicated. It is evident that the standard formulas for torsional, as well as for other forms of resistance, cannot be perfectly correct, since they do not exhibit this difference in the character of the resistance offered by ductile and by rigid materials.

The *elasticity* of the material is determined by relaxing the distorting force, at intervals, and allowing the specimen to relieve itself from distortion so far as its elasticity will permit. In such cases, the pencil will be found to have traced a line resembling, in its general

form and position, in respect to the coördinates, that forming the initial portion of the diagram, but almost absolutely straight, and more nearly vertical. The degree of inclination of this line indicated the elasticity, precisely as the initial straight line was made to give a measure of the original stiffness of the test piece, the cotangent of the angle made with the vertical, $Cot.\ \Phi = \frac{1}{Tan.\ \Phi}$ being the ratio of the force required to spring the piece through the range recoverable by elasticity, to the magnitude of that range. The fact, to be shown, that this value is always greater than $Cot.\ \Theta$, for the same metal is evidence that more or less permanent set will always occur, and that the original stiffness of the specimen is always modified, whatever the magnitude of the applied force. The form of the line of elastic change indicates also the character of the molecular action producing it.

Finally, the form of the curve after passing the maximum, or after passing the point at which fracture commences, exhibits the method of variation of strength during the process of fracture. This portion is very difficult to obtain, with even approximate accuracy, with any but the toughest and most ductile materials. This terminal portion of the diagram would be, theoretically, a cubic parabola, the loss of resisting power varying with the progressive rupture of concentric layers, and the remaining unbroken cylindrical portion becoming smaller and smaller until resistance vanishes with the fracture of the axial line. In some cases, the curves obtained from ductile metals exhibit this parabolic line very distinctly. In all hard materials, the jar produced by the sudden rupture of surface particles is sufficient to separate those within, and the terminal line is straight and vertical.

The *homogeneity* of the material tested is frequently hardly less important than its strength, and it is very desirable to obtain evidence which may enable the experimenter to determine the value of tests of samples as indicative of the character of the lot from which the specimens may have been taken. If the specimens are found to be perfectly homogeneous, it may be assumed with confidence that they represent accurately the whole lot. If the samples are irregular in structure and in strength, no reliable judgment of the value of the lot can be based upon their character, and there can be no assurance that, among the pieces accepted, there may not be untrustworthy material which may possibly be placed just where it is most important to have

the best. It is evident that the more homogeneous a material, the more regularly would changes in its resistance take place, and the smoother and more symmetrical would be the diagram. The depression of the line immediately after passing the elastic limit exhibits the greater or less homogeneousness of the material. The fact is illustrated in a striking manner in some of the curves presented, and we thus have—what had never, I believe, been before found—this method of determining homogeneousness.

The *resilience* of the specimen is measured by the area included within its curve, this being the product of the mean force exerted into the distance through which it acts in producing rupture, *i. e.*, it is proportional to the work done by the test piece in resisting fracture, and represents the value of the material for resisting shock. The area taken within the ordinate of the limit of elasticity, measures the capacity for resisting shock without serious distortion or injurious set.

The *ductility* of the specimen is deduced from the value of the total angle of torsion, and the measure is the elongation of a line of surface particles, originally parallel to the axis, which line assumes a helical form as the test piece yields, and finally parts at or near the point where the maximum resistance is formed. Its value is given on Plates II and III for each ten degrees of arc. Since, in this case, there is no appreciable reduction of section, or change of form, in the specimen, this value of elongation is our actual measure of the maximum ductility of the material, and is an even more accurate indication than the area of fractured cross section as usually measured after rupture by tension. It is to be understood that wherever comparisons are here made, without the express statement of other conditions, that specimens of the same dimensions are always represented in the diagrams.

5. Description of Illustrated Diagrams. The Woods.*—Plates I and II exhibit sets of curves which illustrate the general characteristics of a large number of materials, the first showing the peculiarities noted during experiments on the woods, and the second giving an interesting comparison of the metals.

*The section describing the woods is partly similar to that previously published in the "Journal of the Franklin Institute," and is here reprinted, *to preserve the present more elaborate treatise unbroken, and because the study of the several plates, and their comparison was considered essential to a thorough understanding of the subject.*—Ed.

The woods experimented upon were the following, the numbers of the respective curves on Plate I, indicating the material here correspondingly marked:

1. White pine (*Pinus Strobus*).
2. Southern pine (*Pinus Australis*), sap wood.
3. Southern pine, heartwood.
4. Black spruce (*Abies Nigra*).
5. Ash (*Fraxinus Americanus*).
6. Black walnut (*Juglans Nigra*).
7. Red cedar (*Juniperus Virginianus*).
8. Spanish mahogany (*Swietenia Mahogani*).
9. White oak (*Quercus Alba*).
10. Hickory (*Carya Alba*).
11. Locust (*Robinia Pseudo-acacia*).
12. Chestnut (*Castanea Vesca*).

The specimens were all of the form shown in Fig. 3, three and three-fourths inches long, with a diameter of neck of seven-eighths of an inch.

It will be noticed that, in all cases, at the commencement of the line, it rises, at a slight inclination from the vertical, and almost perfectly straight. This confirmation of Hooke's law, within the limit of elasticity, is best shown in the detached portion *a*, *a*, *a*, of the curve obtained with locust, in which the horizontal scale is somewhat magnified. The distortion is seen to be very precisely proportional to the distorting force, until the law changes at the limit of elasticity.

It will be observed that, in the larger number of cases, the torsional resistance increases with great regularity nearly to the angle of maximum stress where, suddenly, this rapid rate of increase ceases, and the limit of elastic resistance being passed, resistance diminishes rapidly with further increase of angular movement, until it becomes zero. In the tougher and more dense varieties, this decrease of resistance occurs less slowly, and in some cases only disappears after a large angle of torsion is recorded. In the curves of exceptionally strong and tough woods, in which there is known to exist a great excess of longitudinal over lateral cohesion, as in those of black walnut 6, 6, locust 11, 11, and especially in those of hickory 10, 10, a peculiarity is perceivable which is somewhat remarkable, and which is especially important in a connection to be hereafter referred to at length.

In these instances the resistance is proportional to the amount of

torsion, until a maximum is reached, the line then falls as torsion continues, until a minimum is passed, the curve then again rising and passing another maximum before finally commencing an unintermitted descent to the axis of abscissas. Where the difference between longitudinal and lateral cohesion is exceptionally great, the second maximum may, as illustrated, for example, by the line described in recording the test of hickory, have a higher value even than the first. This interesting and previously unanticipated peculiarity was shown, by careful observation, to be due to the sudden yielding of lateral cohesion when the torsional moment reached the value indicated by the first minimum. The fibres being thus loosened from each other, this loose bundle of filaments yielded readily, until, by lateral crowding as they assumed a helical form and enwrapped each other, their slipping upon each other was gradually checked, and resistance again commenced increasing.

At the second maximum, yielding again began in consequence of the breaking of fibres under the longitudinal stress measured by that component of torsional force having a direction parallel with the filaments in their new positions, the exterior surface threads parting first under this tensile stress, and rupture progressing by the yielding of layer after layer, until the axial line being reached, resistance vanished. In this case, rupture seems never to occur by true shearing along one defined transverse plane. This feature of depression in the curve, occurring as described, is therefore the indication of a lack of symmetry in the distribution of resisting forces. It is evident that it may occur either by a difference in the value of cohesive force in the lateral and longitudinal directions, or by the structural defects of a specimen in which the substance itself may be endowed with cohesion of equal intensity in all directions.

The curves shown in Plate I exhibit well the relative values of these materials for the various purposes of the engineer.

White pine, 1, 1, 1, is shown by the considerable inclination of the line of stiffness from the vertical, to be soft and deficient in rigidity. The limit of elasticity is quickly reached, and the maximum resistance of the specimen is found at 15½ foot-pounds of moment. Rapidly losing strength after passing the limit of resistance, it is entirely broken off at an angle of 130°. The small area comprised by the diagram proves its deficiency of resistance, and its inability to sustain shock.

Yellow pine, 2, 2, 2, 3, 3, 3, far excels the first in all valuable pro-

perties shown by the curve. The sapwood seems, in the specimens tested, equally stiff with the heart, but it reaches the elastic limit sooner. The general form of the diagram is the same in both, and is characteristically different from that of the white pine. It evidently has great value wherever rigidity, strength, toughness and resilience are desired in combination with lightness, the latter most important quality, together with their cheapness, aiding the qualities here shown in determining the application of these woods so extensively for general purposes. It should be noted that, since all comparisons of strength are based on measures of volume, a comparison of densities should usually be obtained to assist the judgment in making a choice from among materials of which tests have been made.

Spruce, 4, 4, 4, while possessing far less stiffness than even white pine, excels it somewhat in strength, passing its maximum at 18 foot-pounds, and submitting to a torsion of nearly 200°. It is proven to possess proportionally greater resilience also. It is, however, far inferior to the yellow pine in every respect.

Ash, 5, 5, 5, is more deficient in strength and toughness than is generally supposed, and rapidly loses its power of resistance after passing the maximum, which point is found at about 27½ foot-pounds. These specimens may have been of exceptionally poor quality, or, possibly, were over-seasoned.

Black walnut, 6, 6, 6, is remarkably stiff, strong and resilient, its diagram resembling somewhat that of oak in general form and dimensions. The maximum of resistance reaches 35 foot-pounds, and the most ductile specimen was only broken off after yielding through an arc of 220°. Its stiffness is shown by the fact that it required a moment of 25 foot-pounds to spring it 10°, yellow pine requiring but 22 foot-pounds and spruce but 8, to give them the same amount of distortion.

Red cedar, 7, 7, 7, is very stiff, but is brittle and deficient in strength, breaking off at 92°, and having a maximum power of resistance of but 20½ foot-pounds. It is, however, one of the stiffest of the woods, its specimen requiring 29 foot-pounds of torsional moment to produce a total angle of torsion of but 5°.

Spanish mahogany, 8, 8, 8, is both strong and stiff, bearing a stress of 44 foot-pounds, and requiring 32 to produce torsion of 10°.

White oak, 9, 9, 9, exhibits less strength than either good mahogany, locust or hickory, but it is exceedingly tough and resilient. Passing the maximum at an angle of 15°, under a torsional stress of

35½ foot-pounds, it retains its power of resistance nearly unimpaired up to about 70°, and then slowly yields until it suddenly gives way, after passing the angle 250°, under a strain due to 9 foot-pounds, and breaks off completely at 253°. This strength, toughness and endurance, under strains due to impact, may be attributed to its considerable lateral cohesion, and to the interlacing of its tenacious fibres, which gives this wood its "cross" grain.

Hickory, 10, 10, 10, has the highest maximum found during these experiments, the second of the pair of maxima already referred to being considerably above the maximum of locust even. This specimen exhibits well the well-known valuable properties of the material, requiring 45 foot-pounds to twist it 10°, reaching a limit of elasticity at 54 foot-pounds and 13°, and having a maximum resisting moment of 59½ foot-pounds. When it finally yields, it does so quite rapidly, breaking off at 145°.

Locust, 11, 11, 11, gives an excellent diagram. It is the stiffest of all, yielding but 10° at its maximum of 55 foot-pounds, and one piece, which was unusually hard and compact, requiring 48 foot-pounds to distort it 4°, and reaching a maximum angle of torsion of nearly 190°.

It was noticed, during this series of experiments, that different specimens of the same species of wood usually exhibited very nearly equal strength and rigidity, and that marked differences were only occasionally noted in elasticity and resilience.

6. The Metals, and the Curves produced by them.—Plate II exhibits a series of curves which illustrate well the general characteristics and the peculiarities of representative specimens of the principal varieties of useful metals. In some cases two specimens have been chosen for illustration, of which one presents the average quality, while the other is the best and most characteristic of its class.

The diagrams obtained by testing metals are quite different in general character from those registered in experiments on the woods, yet there are some points of resemblance which it will be instructive to notice, since these similar characteristics indicate similar properties of the two materials, and a comparison aids greatly in the interpretation of the diagrams. The woods have a structure which differs, in a distinguishing degree, both in the distribution of the substance and in the action of these molecular forces capable of resisting rupture, from that of the metals, the latter being far more homogeneous, in both respects, than the former. Wood consists of an aggregation

of strong fibres, lying parallel, or approximately so, and held together often by a comparatively feeble force of lateral cohesion. The latter force being, as often happens, destroyed, the mass becomes a collection of loose threads having the general character of a rope or cord, with slight or no twist. The metals, on the other hand, are naturally homogeneous, both in structure and in the distribution and intensity of the molecular forces. Well-worked and thoroughly annealed cast-steel, as an example, is equally strong in all directions, is perfectly uniform in its structural character, and is almost absolutely homogeneous as to strain. It would be expected, therefore, that the diagrams obtained by breaking such a material would differ from those of the woods, in having a smoother and more regular form, and this is shown to be actually the case by observation of the curves of cast-steel, cast-iron, bronze and others of the more homogeneous metals and alloys.

Some of the metals, it will be noticed, yield diagrams of less regular form. Wrought iron, as usually made, has a somewhat fibrous structure, which is produced by particles of cinder, originally left in the mass by the imperfect work of the puddler while forming the ball of sponge in his furnace, and which, not having been removed by the squeezers or by hammering the puddle ball, are, by the subsequent process of rolling, drawn out into long lines of non-cohering matter, and produce an effect upon the mass of metal which makes its behavior, under stress, somewhat similar to that of the stronger and more thready kinds of wood. In the low steels, also, in which, in consequence of the deficiency of manganese accompanying, almost of necessity, their low proportion of carbon, this fibrous structure is produced by cells and "bubble holes" in the ingot, refusing to weld up in working, and drawing out into long microscopic, or less than microscopic, capillary openings.

In consequence of this structure we find, as we should have anticipated, a depression interrupting the regularity of their curves, immediately after passing the limit of elasticity, precisely as the same indication of the *lack of homogeneousness of structure* was seen in the diagrams produced by locust and hickory.

The presence of internal strain constitutes an essential peculiarity of the metals which distinguishes them from organic materials. The latter are built up by the action of molecular forces, and their particles assume naturally, and probably invariably, positions of equilibrium as to strain. The same is true of naturally formed organic sub-

stances. The metals, however, are given form by external and artificially produced forces. Their molecules are compelled to assume certain relative positions, and those positions may be those of equilibrium, or they may be such as to strain the cohesive forces to the very limit of their reach. It even frequently happens, in large masses, that these internal strains actually result in rupture of portions of the material at various points, while in other places the particles are either strongly compressed, or are on the verge of complete separation by tension. This peculiar condition must evidently be of serious importance, where the metal is brittle, as is illustrated by the behavior of cast-iron, and particularly in ordnance. Even in ductile metals it must evidently produce a reduction in the power of the material to resist external forces. This condition of internal strain may be relieved by annealing hammered and rolled metals, and by cooling castings very slowly, in order that the particles may assume, naturally, positions of equilibrium. In tough and ductile metals, internal strain may be removed by heating to a high temperature and then cooling under the action of a force approximately equal to the elastic resistance of the substance. This process, called "Thermo-tension," was first used by Professor Johnson in the course of his experiments as a member of a Committee of the Franklin Institute, in 1836,* and the effect of this action in apparently strengthening the bars so treated, was stated in the report of the committee. The fact that this effect was very different with different kinds of iron was also noted, but it does not appear that the cause of this, which they term "an anomalous" condition of the metal was discovered by them.

Metals which are very ductile may frequently be relieved of internal strain, also, by simply straining them while cold to the elastic limit, and thus dragging all their particles into extreme positions of tension, from which, when released from strain, they may all spring back into their natural and unstrained positions of equilibrium. This fact, which does not seem to have been previously discovered by investigators of this subject, will be seen to have an important bearing upon the resisting power of materials, and upon the character of all formulas in which it may be attempted to embody accurately the law of resistance of such materials to distorting or breaking strain.

Since straining the piece to the limit of elasticity brings all particles subject to this internal strain into a similar condition, as to strain, with adjacent particles, it is evident that indications of the existence

* Journal Franklin Institute, 1836–7.

of internal strain, and through such indications a knowledge of the value of the specimen, as effected by this condition, must be sought in the diagram, before the sharp change of direction which usually marks the position of the limit of elasticity is reached. As already seen, the initial portion of the diagram, when the material is free from internal strain, is a straight line up to the limit of elasticity. A careful observation of the tests of materials of various qualities, while under test, has shown that, as would, from considerations to be stated more fully hereafter, in treating of the theory of rupture, be expected, this line, *with strained materials, becomes convex towards the base line*, and the form of the curve, as will be shown, is parabolic. The initial portion of the diagram, therefore, determines readily whether the material tested has been subjected to internal strain, or whether it is homogeneous as to strain. This is exhibited by the *direction* of this part of the line as well as by its form. The existence of internal strain causes a loss of stiffness, which is shown by the deviation of this part of the line from the vertical to a degree which becomes observable by comparing its inclination with that of the line of elastic resistance, obtained by relaxing the distorting force —*i. e.*, the difference in inclination of the initial line of the diagram and the lines of elastic resistance, *e*, *e*, *e*, indicates the amount of existing internal strains.

Forged Iron.—In Plate II, the curves numbered 6, 1, 22 and 100 are the diagrams produced by three characteristic grades of wrought-iron. The first is a quality of English iron, well known in our market as a superior metal. The second is one of the finest known brands of American iron, and the third is also of American make, but it does not usually come into the market in competition with well-known irons, in consequence of the high price which is consequent upon the necessary employment of an unusual amount of labor, in securing its extraordinarily high character.

No. 6 at first yields rapidly under moderate force, only about 50 foot-pounds of torsional moment being required to twist at 5°. It then rapidly becomes more rigid, as the internal strains, so plainly indicated, are lost in this change of form, and at 6° of torsion, the resistance becomes 60 foot-pounds, as measured at *a*. Here the elastic limit is reached. The next 3° produce no increase of resistance. The fact shows that this iron, which was not homogeneous as to strain, is also not homogeneous in structure. We conclude that it must be

badly worked and seamy, and that it may have been rolled too cold; the former is the probable reason of its lack of homogeneous structure, the latter gave it its condition of internal strain. After the first 9° of torsion, resistance steadily rises to a maximum, which is reached only when just on the point of rupture, and the piece finally commences breaking at 250°, and is entirely broken off at 285°. Its maximum elongation, whose value is proportionable to the reduction of section noted with the standard testing machines, is 0·691. The terminal portion of the line, after rupture commences, is not usually accurate as a measure of the relation of the force to the distortion. The increase of resistance between the angle 9° and the angle of rupture is produced by the additional effort in resistance due to the "flow" or drawing out of particles, as already indicated, and the precise effect of which will be noticed at length in a succeeding section relating to the theory of rupture.

Applying the scale for tension, which in the case of these curves was very exactly 24,000 pounds per square inch for each inch measured vertically on the diagram, we find that the elastic limit was passed under a stress equivalent to a tension of 19,800 pounds per square inch, and that the ultimate tenacity was 59,200 pounds per square inch. When nearly at the maximum the specimen was relieved from stress, the pencil descending to the base line, and the elasticity of the piece produced a certain amount of recoil. The angle intercepted between the foot of this nearly vertical line, *c*, and the origin at *O*, measures the *set*, which is almost entirely permanent. The distance measured from the foot of the perpendicular, let fall upon the axis of abscissas, from the head of this line to the foot of the line *e*, measures the elasticity, *and is inversely proportional to the modulus.* A comparison of the inclination of the line made by the pencil in reascending, on the renewal of the strain with the initial line of the diagram, gives the indication of the amount of internal strain originally existing in the piece.

It will be noticed that the horizontal movement of the pencil is recommenced at *I*, under a higher resistance than was recorded before the elastic line was formed. In this case the piece had been left under strain for some time before the stress was relieved, and the peculiarity noted is an example of an increase of resistance under stress,* or more properly of *the elevation of the elastic limit*, of which more marked examples will be shown subsequently.

* *Vide* Transactions, Vol. II, page 290.

The exceptional stiffness and limited elastic range here shown, as compared with the other examples given, is probably a phenomenon accompanying and due to this increase of resistance under stress.

Examining No. 1 in a similar manner, we find that it is far freer from internal strain than No. 6, its initial line being much more nearly straight and rising more rapidly. It is rather less homogeneous in structure, and is forced through an arc of 6°, after having passed its elastic limit, before it begins to offer an increasing resistance. It is evidently a better iron, but less well worked, and, as shown by the position of the elastic limit, is somewhat harder and stiffer. No. 1 retains its higher resistance quite up to the point at which No. 6 received its incidental accession of resistance by standing under strain, and the two pieces break at, practically, the same point, No. 1 having slightly the greater ductility. When the "elastic line," *e*, is formed, just before fracture, it is seen that No. 1 has a greater elastic range and a lower modulus than No. 5. It should be observed that the line by which the pencil *descends* to the base line has usually no value, owing to the fact that no care is generally taken to remove the stress as gradually as it is applied. When such care is taken, the lines are usually coincident, and do not form the loop here seen. It will also be noticed that these lines often cross each other, that on the right being the important line. The elastic line formed by No. 1 at between 40° and 45° of torsion is seen to be very nearly parallel with that obtained near the terminal portion of the diagram, and illustrates the fact here first revealed to the eye, that *the elasticity of the specimen remains practically unchanged up to the point of incipient rupture*, and this fact corroborates the deductions of Wertheim* and others who came to this conclusion from less satisfactory modes of research. All experiments yet made give a similar result.

No. 22 illustrates the characteristics of a metal which probably represents one of the best qualities of wrought iron made in this or in any other country, and with which every precaution has been taken to secure the greatest possible perfection, both in the raw material and in its manufacture. The fact that it finds a market at sixteen cents a pound proves that even such care and expense are well applied. The line of this diagram, starting from *O*, rising with hardly perceptible variation from its general direction, turns, at the elastic limit, *a*, under a moment of about 80 foot-pounds, equivalent to a

* *Vide* Annales de Chimie et de Physique.

tension of about 24,000 pounds per square inch; and with between 2° and 3° of torsion only, and thence continues rising in a curve almost as smooth and regular as if it had been constructed by a skilful draughtsman. Reaching a maximum of resistance to torsion of 220 foot-pounds and an equivalent tensile resistance of over 66,000 pounds per square inch, at an angle of 345°, it retains this high resistance up to the point of rupture some 358° from its starting point. The maximum elongation of its exterior fibres is 1·2, making them at rupture 2·2 times their original length. This would produce a probable breaking section in the common testing machine equal to 0·4545 of the original section.†

From the beginning to the end this specimen exhibits its superiority, in all respects, over the less carefully made irons, Nos. 1 and 6, which, it should be remembered, are themselves deservedly known as good brands. The homogeneousness of No. 22 is almost perfect, both in regard to strain and to structure, the former being indicated by the straightness of the first part of the diagram and its parallelism with the "elastic line," *e*, produced at 217½°, and the latter being proven by the beautiful accuracy with which the curve follows the parabolic path indicated by our theory as that which should be produced by a ductile homogeneous material. At similar angles of torsion, No. 22 offers invariably much higher resistance than either Nos. 1 or 6, and this superiority, uniting with its much greater ductility, indicates an immensely greater resilience. It is evident that for many cases, where lightness combined with capacity to carry live loads and to resist heavy shocks are the essential requisites, this iron would be by far preferable, notwithstanding the cost of its manufacture, to any of the cheaper grades. Comparing their elasticities, as shown at 210°, 215°, it is seen that No. 22 is about equally stiff and elastic with No. 1, while both have a wider elastic range and are less rigid, and hence are softer than No. 6, whose elastic line is seen at 221°. All of the characteristics here noted can be accurately gauged by measuring the diagrams, and constants are readily obtained for all formulas, as illustrated in a later section of this paper, in which the construction of formulas and the determination of constants will be made the subject of investigation.

† Compare Kirkaldy: Strength of Iron and Steel; pp. 111, 135, for reduction in Yorkshire and Swedish bars. The elongation there given has, of course, no value as a measure of ductility.

No. 100 is the curve obtained from a piece of Swedish iron, marked GF. Its characteristics are so well marked that one familiar with the metal would hardly fail to select this curve from among those of other irons. Its softness and its homogeneous structure are its peculiarities. Its curve, at first, coincides perfectly with that of No. 6. It has, however, slightly less of the condition of internal strain, and a somewhat higher limit of elasticity. The elastic limit is found at $5\frac{1}{2}°$ of torsion, and at a stress of 65 foot-pounds of moment, equivalent to 19,500 pounds on the square inch, in tension. Its increase of resistance, as successive layers are brought to their maximum and begin to flow, is very nearly the same as that of the specimens Nos. 1 and 6, and the line lies between the diagrams given by these irons up to 30°, and then falls slightly below the latter. At 220°, it attains a maximum resisting power, and here the outer surface begins to rupture, after an ultimate stretch, of lines formerly parallel to the axis, amounting to 0·564. Had this elongation taken place in the direction of strain, as in the usual form of testing machine, it would have produced a reduction of section to 0·64, the original area.* At this point the stress in tension equivalent to the 176 foot-pounds of torsional stress, is 52,800 pounds per square inch. From 250° the loss of resistance takes place rapidly, but the actual breaking off of the specimen did not occur until it had been given a complete revolution. This part of the diagram distinguishes the metal from all others, and shows distinctly the exceptionally tough, ductile and homogeneous character which gives the Swedish irons their superiority in steel making. No. 22, even, although much more extensible, is harder than No. 100, and yields more suddenly when it finally gives way.

A comparison of the results here recorded with those obtained by Styffe,† will afford a good basis upon which to form an idea of the accuracy as well as the convenience of this method of deriving them. An examination of the broken test piece gives some evidence confirmatory of the record. The exterior surface of the twisted portion has an appearance intermediate between that of No. 1, Fig. 5,‡ and No. 22, Fig. 7, with an evident tendency to "kink." The surface of fracture is lighter and more lead-like than even No. 22, and its

* Compare Styffe; Strength of Iron and Steel; p. 133, Nos. 26—30.

† As on last page.

‡ From an article in the "Scientific American," of January 17th, 1874, on Testing the Quality of Iron, Steel and other Metals without Special Apparatus.

"fibre" is finer and texture more plastic in appearance. It is beautifully uniform in character. On one end of this specimen, where a piece had been nicked and then broken off by a sharp blow, the absence of all fibrous appearance, and the granular texture and magnificently fine, regular grain are very marked, and indicate that the material is entitled to its established position as the purest metal known in the market. The specimens themselves furnish almost as valuable information, after test, as the diagrams contain, and should always be carefully inspected with a view to securing additional or corroborative information. Fig. 5 is a sketch of specimen No. 1, and shows its somewhat granular fracture, and the seamy structure produced by a defective method of working. Fig. 6, from specimen No. 16, more nearly resembles that which gave the diagram marked 6. The metal is seen to be good, tough, and better in quality than No. 1, but it is even more seamy, and even less thoroughly worked, as is evidenced by the cracks extending around the neck, and by the irregularly distributed flaws seen on its end.

Fig. 5.

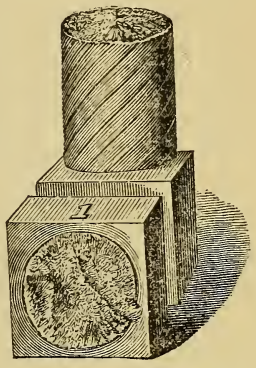
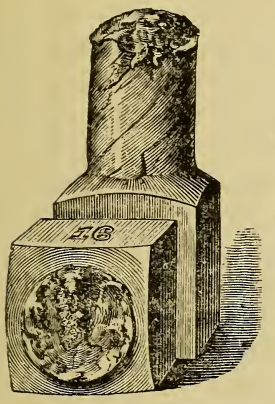
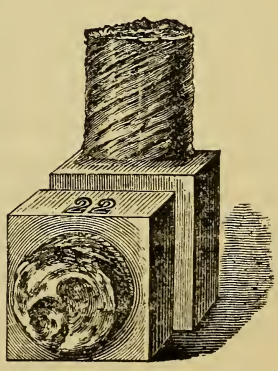


Fig. 6.



No. 7 exhibits the appearance of No. 22 after fracture, and shows, even more perfectly than the pencilled record, the splendid character of the material. The surface of the neck was originally smoothly turned and polished, and carefully fitted to gauge. Under test it has become curiously altered, and has assumed a rough, striated appearance, while the helical markings extend completely around it. The end has the peculiar appearance which will be seen to be characteristic of tough and ductile metals, and the uniformly bright appearance of every particle in the fractured section shows how all held to-

Fig. 7.



gether up to the instant of rupture, and that fracture finally took place by true shearing. Rupture by torsion thus brings to light every defect and reveals every excellence in the specimen. Rupture by tension rarely reveals more than the mere strength of the material.

8.—Low Steels.—In Plate II, and above the curves just described, are a set obtained during experiments on "low steels," produced by the Bessemer and Siemens-Martin processes. In general character, the curves are seen to resemble those of the standard irons, as illustrated by Nos. 1 and 6. The irons contain usually barely a trace of carbon. These steels contain from one-half to five-eighths of one per cent. The irons are made by a process which leaves them more or less injured by the presence of impurities, from which the utmost care can seldom free them. The steels are made from metal which has been molten and cast, a process which allows a far more complete separation of slag and oxides. The low steels, however, are liable to an objectionable amount of porosity, due to the liberation of gas while the molten mass is solidifying, whenever the spiegeleisen, employed as a conveyor of carbon, is not very rich in manganese. The results of these differences in constitution and treatment are readily seen by inspecting the curves. They show a stiffness equal to No. 6, and about the same degree of internal strain. They contain a sufficient number of the capillary channels, produced by drawing down the pores while working the ingot into bar, to cause a lack of homogeneousness in structure, very similar to that produced in iron by cinder. They have a much higher elastic limit, and greater strength, and the softer grades have great ductility. In resilience, these softest steels excel all other metals, except the unusual example, No. 22, and are evidently the best materials that are now obtainable for all uses where a tough, strong, ductile metal is needed to sustain safely heavy shocks. A comparison of the diagrams of two competing metals may thus be made to indicate how far a difference in price should act as a bar to the use of the costlier one. For many purposes, a metal having double the resilience of another is worth more than double-price. For general purposes, a comparison of the resilience of the metals within the elastic limit is of supreme importance. No. 6 is seen to have more resilience within this limit than No. 1, and the steels far more than either; but No. 1 would take a set of considerable amount far within the true elastic limit, as indicated at *a*. The most valuable measure is obtained by determining the area intercepted between the

"elastic line" and the perpendicular let fall from its upper end; this measures the resilience of elastic resistance, which is the really important quality.

No. 98 was cut from the head of an English Bessemer rail made from unmixed Cumberland ores. It contains nearly 0·4 per cent. carbon. It is quite homogeneous, has a limit of elasticity at 88 foot-pounds of torsional, or 26,400 pounds per square inch tensile stress, approaches its maximum of resistance rapidly, and, at 210°, the torsional moment becomes 225 foot-pounds, equivalent to 67,500 pounds per square inch tensile stress. It only breaks after a torsion of 283°, and with an ultimate elongation of 80 per cent., equivalent to a reduction of cross section to 0·556.

No. 76 is a Siemens-Martin steel made from mixed Lake Superior and Iron Mountain ores, and contained about the same amount of carbon as the preceding. It contains rather more phosphorus, which probably gives it its somewhat greater hardness, its higher limit of elasticity and its somewhat reduced ductility. Its elastic limit is found at 104 foot-pounds of torsion, or 31,200 pounds tensile resistance, and its ultimate strength is almost precisely that of the preceding specimen. Its elongation is 0·66 maximum. Unless more seriously affected by extreme cold than No. 98, it would be preferred for rails, and, perhaps, for most purposes.

No. 67 is a somewhat "higher" steel, made by the same process. It is less homogeneous than the two just examined, has greater strength and a higher elastic limit, but less ductility. Its resilience is very nearly the same as that of Nos. 98 and 76. The elasticity of all of these steels seems very exactly the same. The ductility of No. 67 is measured by 0·40 elongation. At *d*, is seen another illustration of elevation of the elastic limit. The piece was left twenty-four hours under maximum stress. The torsional force was then removed entirely. On renewing it, as is seen, the resistance of the specimen was found increased in a marked degree.

No. 69 is an American Bessemer steel, containing not far from 0·5 per cent. carbon. The same effect is seen here that was before noted, an increase of hardness, a higher elastic limit, and greater strength, obtained, however, by some sacrifice of both ductility and resilience. The elastic limit is approached at 130 foot-pounds of torsional moment, or 39,000 pounds tensile, and the maximum is 280 foot-pounds of moment and 84,000 pounds tensile resistance at 133°. Its maximum angle of torsion is 150°, its elongation 0·24.

No. 85 is a singular illustration of the effects of what is probably a peculiar modification of internal strain. It seems to have no characteristics in common with any other metal examined. Its diagram would seem to show a perfect homogeneousness as to strain, and a remarkable deficiency of homogeneity in structure. It begins to exhibit the indications of an elastic limit at *a*, under a torsional moment of 110 foot-pounds, or an apparent tensile stress of 33,000 pounds per square inch, and then rises at once by a beautifully regular curve, to very nearly its maximum at 16°, and 176 foot-pounds. The maximum is finally reached at 130°, and thence the line slowly falls until fracture takes place at 195°. The maximum resistance seems* to be very exactly 60,000 pounds to the square inch. Its maximum elongation for exterior fibres is about 0·23. The resilience taken at the elastic limit is far higher than with common iron, and it is seen that this metal, in many respects, may compete with steel. Its elasticity is seen to remain constant wherever taken. This singular specimen was a piece of "cold rolled" iron. It is probably really far from homogeneous as to strain, but its artificially produced strains are symmetrically distributed about its axis, and being rendered perfectly uniform throughout each of the concentric cylinders into which it may be conceived to be divided, the effect, so far as this test, or so far as its application as shafting, for example, is concerned, is that of perfect homogeneousness. The apparently great deficiency of homogeneousness in structure is readily explained by an examination of the pieces after fracture; they are fibrous, and have a grain as thread-like as oak; their condition is precisely what is shown by the diagram, and the metal itself is as anomalous as its curve.

8.—Tool Steels.—The "tool steels" differ chemically from the "low steels" in containing a higher percentage of carbon, and usually, in being very nearly, if not absolutely, free from all injurious elements. They are made in crucibles by melting down the blister steels which are the crude product of the process of cementation, or sometimes, by melting a charge composed of selected iron, a small proportion of manganese bearing alloy and the proper amount of carbon. Containing a higher proportion of carbon than the preceding class of metals, it is comparatively easy to secure homogeneousness by the introduction of manganese, and by the same means, to eliminate very per-

* With an exceptional case, of which this is an example, the scale for tension s incorrect. The tensile strength is probably higher than here given.

fectly the evil effects of any small proportion of sulphur that may be present. Their comparatively large admixture of carbon makes them harder, and reduces their ductility, and since the reduction of ductility occurs to a greater degree than the increase of strength, the effect is also to reduce their resilience. The working of these metals is more thorough than is that of the less valuable steels, or of iron. They are cast in comparatively small ingots, and are frequently drawn down under the hammer, instead of in the rolls, and are thus more completely freed from that form of irregularity in structure noticed so invariably in steels otherwise treated. The effect of increasing the proportion of carbon, is to confer upon iron the property of hardening, when heated to a high temperature, and suddenly cooling, and the invaluable property of "taking a temper," *i. e.*, of assuming, under proper treatment, any desired degree of hardness. The hard steels are, however, comparatively brittle, the hardening being secured at the expense of ductility. The effect produced upon the tenacity of unhardened steel, by increasing proportions of carbon, is somewhat variable, since it is influenced greatly by the presence of other elements. For good steels unhardened, the writer has been accustomed to estimate tenacity by the following formula, which is approximately accurate, and may be often found useful:

$$T = 60{,}000 + 70{,}000\ C.$$

in which T represents the tenacity in pounds per square inch, and C is the percentage of carbon contained in the metal. This subject will be considered at greater length after a series of experiments have been made to obtain more exact determinations.

Referring to Plate II, a set of diagrams will be found, having their origin at 180°, which are *fac similes* of those automatically produced during experiments upon various kinds of tool steels.

No. 58 is an English metal, known in the market as "German crucible steel." It is remarkable as having a condition of internal strain which has distorted its diagram to such an extent as to completely hide the usual indication of the elastic limit. A careful inspection shows what may be taken for this point at about 14½° of torsion, when the twisting moment was about 120 foot-pounds, and the tensile resistance 36,000 pounds per square inch. The metal is homogeneous in structure, has an ultimate resistance of 302 foot-pounds of moment, or 90,600 pounds per square inch tensile resistance. Its resilience is evidently inferior to that of the softer metals, and also less than the next higher and better grades. This metal

contains about 0·60 to 0·65 per cent. carbon. Its elongation amounts to 0·045.

No. 53 is an English "double shear steel," of evidently very excellent structure, but less strong and less resilient than the preceding. Its exterior fibres are drawn out three per cent.

Nos. 41 and 61 are two specimens of one of the best English tool steels in our market. The first was tested as cut from the bar, but the second was carefully annealed before the experiment. In this instance, annealing has caused a slight loss of resilience as well as a decided loss of strength. In No. 41, the limit of elasticity can hardly be detected, but seems to be at about the same point as in No. 61, at near 130 foot-pounds moment and 39,000 pounds tension. The ultimate strength is nearly 119,000 pounds per square inch. The proportion of carbon is very closely 1 per cent. Its section would reduce by tension, 0·05.

No. 70 is an American "spring steel," rather hard, but as shown by its considerable resilience, of excellent quality, resembling remarkably the tool steel No. 41. It differs from the latter, apparently by its much higher elastic limit. It is possible that this may have been caused by more rapidly cooling after leaving the rolls in which it was last worked. It is evident that, for exact comparison, all specimens should be either equally well annealed or should be tempered in a precisely similar manner, and to the same degree.

Nos. 71 and 82 are American tool steels, containing about 1·15 of carbon. The former is notable as having an elastic limit at 69,000 pounds, and a probable deficiency of manganese, producing the usual indication of heterogeneous structure. Both of these steels lack resilience, and are less well adapted for tools like cold chisels, rock drills, and others which are subjected to blows, than for machine tools. They have a maximum elongation, respectively, of but 0·013 and 0·03.

Interesting and instructive as the study of these curves may be made, the information obtained from them is supplemented, in a most valuable manner, by that obtained by the inspection of the fractured specimens, upon which the peculiar action of a torsional strain has produced an effect in revealing the structure and quality of the metal that could be obtained in no other way.

Fig. 8 represents the appearance of No. 68, and Fig. 9 that of No. 58, while the peculiarities of the finest tool steels are seen in No. 71,

Fig. 8.

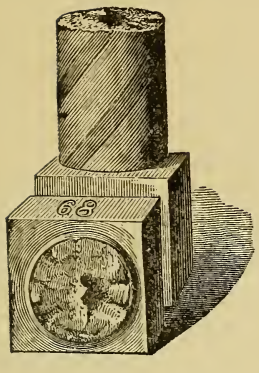


Fig. 9.

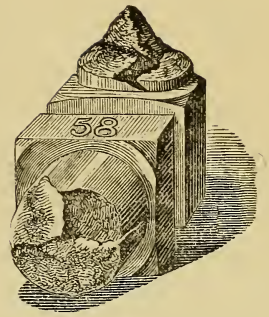
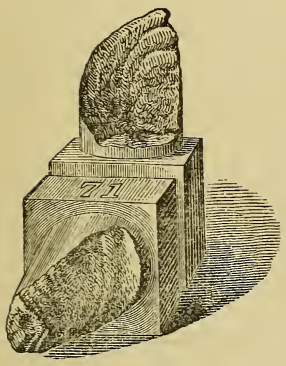


Fig. 10.



as shown in Fig. 10. The smooth exterior of No. 68, which is a companion specimen to that giving diagram 69, and its bright and characteristic fracture, resembling that of No. 22 somewhat, together indicate its nature perfectly, the first feature proving its strength and uniformity of structure, and the second showing, even to the inexperienced eye, its toughness. This is a representative specimen of low steels. No. 58 is seen to have retained, even more than No. 68, its original smoothly polished surface. Its fracture is less waxy, and much more irregular and sharply angular. The crack running down the side of the neck shows its relationship to the shear steels which much oftener exhibit this effect of strain, in consequence of their lamellar character. No. 58 is evidently intermediate in its character between the soft steels, like No. 68, and the tools steels which are represented by No. 71, Fig 10. In this test-piece, the fracture is ragged and splintery, and the separated surfaces have a beautifully fine, even grain, which proves the excellence of the material. The surface which was turned and polished in bringing the metal to size remains as perfect as before the specimen was broken. By an inspection of the broken test-pieces in this manner, the grade of the steel, and such properties also as are not revealed by an examination of the diagram of strain, are very exactly ascertained by a novice, and to the practical eye, the slightest possible variations are readily distinguishable.

9. Cast-iron.—The diagrams of strain having their commencement at 100°, have been obtained from cast-iron and from malleableized cast iron.

Nos. 23 and 24 are those given by a good dark grey foundry iron from Pennsylvania. No. 25 represents the curve of light grey scrap, and 30 is from a very fine white Lake Superior charcoal iron. The latter is seen to be exceedingly hard and rigid, the resistance of the piece rising very precisely in proportion to the angle of torsion until it snaps at last under a moment of over 200 foot-pounds, equivalent to a tension of 60,000 pounds per square inch, and with a maximum elongation of one-tenth of one per cent. This is a most extraordinary resistance, but it is evident that, notwithstanding its immense strength, this material would be valueless for ordinary purposes in consequence of its excessive brittleness. When the torsional effort had reached about one-half its maximum amount the piece was released. The pencil retreated along a nearly vertical line *e*, which it again traversed as the strain was gradually renewed. Here as in many other cases, where a similar experiment was made, evidence is given of the truth of the statement originally made by Hodgkinson,* that every load produces a set. As will be shown, subsequently, however, it is not true in perfectly homogeneous bodies free from strain, and within their elastic limit. The light grey iron has a limit of elasticity at near one-half the maximum reached by the white iron, without any sign of reaching the limit of its elasticity. The grey has more ductility than the white iron, but has only about two-thirds the resilience of the latter. The dark grey irons are evidently better than either of the lighter grades, except in power of carrying an absolutely static load. The actual stretch of the outer surface particles is very nearly the same in all three. They are excellent specimens of their class, and considerably better than ordinary irons.

No. 37 is a "malleableized cast-iron," made from the extraordinary metal illustrated in No. 30. The process of malleableizing consists in decarbonization by heating the casting made from good white iron, in contact with iron oxide or other decarbonizing material. Without removing any other constituent than the carbon, it produces a crude steel or an impure wrought-iron. When performed in the usual manner, melting the cast-iron in a cupola in contact with the fuel, and with some flux, and then carrying the process of malleableizing to the

* Reports of British Association; also Civil Engineer and Architects' Journal.

usual extent, a metal is obtained such as is illustrated by the diagram marked 37. It retains the strength of the cast-iron, and acquires some ductility.

No. 30 yielded 7° before fracture, while No. 37, vastly more ductile and resilient, only broke after a torsion of 39°, and a maximum elongation of 2 per cent. Taking the precaution to melt the iron in an "air furnace" —a form of "reverberatory"—and conducting the process of malleableizing more carefully, a still more valuable material was obtained.

Fig. 11.

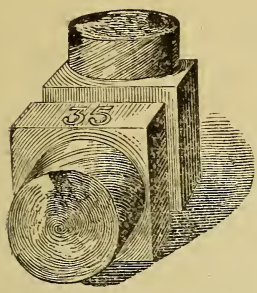
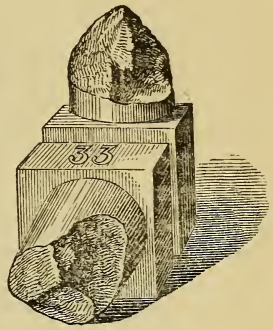


Fig. 12.



No. 35 represents this iron. Its resemblance to wrought-iron, both in appearance of fracture and in its strength and ductility, are greatly increased. It has a high limit of elasticity—over 20,000 lbs. per square inch—and such ductility that it only breaks after a torsion of nearly 168°, and an elongation of "fibre" of 0·35. It is not very homogeneous, but it is as strong, and almost as tough, as a good wrought-iron. This material has especial value for many purposes, because of the facility with which awkwardly shaped pieces can be made of it. In many cases, it will prove as good as wrought-iron and far cheaper.

Fig. 13.

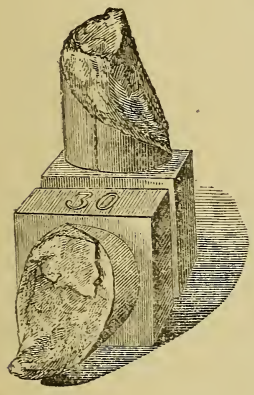


Fig. 14.

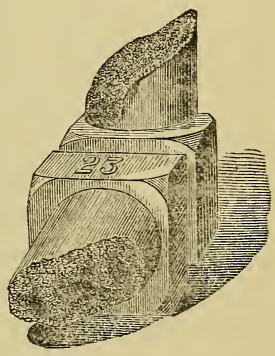


Fig. 11 shows the appearance of this last specimen. Its resemblance to wrought-iron is very noticeable. The lines running like the thread of a screw around the exterior of the neck, and the smooth even fracture in a plane precisely perpendicular to the axis, are the instructive features. Fig 12, representing No. 33, is a specimen similar in character to No. 37. The comparative lack of ductility, its

less regular structure, and its less perfect transformation are perfectly exhibited. Fig 13 is an excellent cut of the white iron as cast and without malleableizing. Its surface, where fractured, has the general appearance of broken tool steel. The color and texture of the metal are distinctive, however. It has none of the "steely grain." Fig. 14 represents the dark grey iron. Its color, its granular structure and coarse grain are markedly characteristic, and no one can fail to perceive, in the specimen, the general character which is exactly given by the autographic diagrams of the testing machine.

10. Other Metals.—The diagrams numbered 87, 88 and 89, are those of copper, tin and zinc. These specimens are all of cast metal, carefully selected under the direction of the writer, and molded and cast at the Stevens Institute of Technology. They exhibit neatly the wonderful superiority which the various kinds of iron and steel possess over the other useful metals. These metals all take a set under very small strains, pass their limits of elasticity at some indeterminable, but evidently low point, and possess very slight tenacity.

Zinc, No. 89, by the regularity of its curve shows a very uniform structure. It increases very gradually in resistance to torsion, until it reaches the angle 50°, at which point it has a moment of torsional resistance of 36 foot-pounds, and a maximum tenacity of about 10,-800 pounds per square inch. It loses its power of resistance, after rupture commences, as regularly, but not as slowly, as it acquired it, and rupture becomes complete at 63°. Its resistance is exceedingly small, and it is evidently unfit to bear either static or dynamic force. Its stretching power has a maximum of 0·04.

Tin, No. 88, is equally remarkable for its exceedingly feeble resistance and its great ductility. The specimen was excellent, both in quality of metal and in closeness of structure, as was indicated by the clearness of the "tin cry" heard while undergoing the test and by the fine, smooth, clean fracture. The character of the curve is similar to that of zinc, but has far greater extent. Its elastic limit is quite indeterminable. The outline of the diagram indicates very perfect homogeneousness. The maximum resistance to torsion is found at 240°, and under a stress of 19 foot-pounds. Its tenacity deduced from the diagram is, at most, but 5,700 pounds per square inch. Rupture occurs very gradually, and the piece separated entirely at 355°. Notwithstanding its great ductility, its low tenacity produces a low resilience, although in this quality it excels zinc, which latter

metal had nearly double its strength. Its elongation by tension would have reduced its section to 0·6 of the original cross area, if that reduction were proportional to the ductility shown by the diagram.

Copper, No. 87, cast in green sand, like the zinc and tin just described, was found, on examination of the fracture, to differ from them in being exceedingly porous. The effect of this fault has been to weaken it seriously. Its curve closely resembles that of zinc, but is abruptly terminated by the piece suddenly breaking off at 46°. It reaches a maximum sooner than zinc, at 29°, and its greatest resistance to torsion is 36 foot-pounds, or to tension 10,800 pounds per square inch, precisely the same as zinc. Its ductility has a value of one and a half per cent. Its resilience is somewhat less than that of zinc. Its limit of elasticity is difficult to determine, but has been taken at 1½° where the moment of resistance is 13 foot-pounds, equivalent very nearly to 3,900 pounds tenacity, per square inch.

No. 134 is the curve of cast copper, precisely similar to No. 87, but cast in a dry sand mold. The marked difference between these specimens is probably due, not only to the difference in degree of porosity which arises from the presence of vapor, which permeates the casting in one case, filling it with bubble holes, and which is almost unobservable in the last, but the slower cooling of the dry sand casting also probably produces its effect in strengthening the metal. This last specimen has a limit of elasticity at not far from 13¾°, and under a torsional stress equivalent to a tension of 5,400 pounds per square inch. The maximum values of these quantities are found at 21°, and are 42 foot pounds, and 12,600 pounds per square inch respectively. The resilience of the specimen is much greater than that of the preceding, and its maximum elongation is ·026. Altogether, this is far betterthan the preceding, and it would seem that copper, and probably all its alloys, should, when possible, be cast in dry sand, to secure density and strength.

No. 141 is a piece of forged copper, hammered into a one-inch square bar, from a piece originally 3½ inches wide and ¾ inch thick. The most striking property noticed is its immense ductility, far exceeding that of any other piece of metal yet tested, and, in amount, many times as great as the cast metal. Its limit of elasticity is reached very quickly, although it is impossible to say precisely where it occurs. Comparing its "elastic line" with the initial portion of the curve, it is seen that the slightest force produces a set which is proportionally large as compared with the sets of other metals. The

curve rises very regularly and gradually to a maximum, which is only attained, however, after a total angle of torsion of 450°, and which measures 96 foot-pounds moment, or 28,800 pounds per square inch. Rupture is finally obtained after a torsion of 543°. The maximum elongation is 210 per cent., the most elongated lines of particles being finally left of 3·1 times their original length. Had this change of form occurred by reduction of section, the fractured area would have been but ·323 the area of original section. The resilience of this piece of metal is evidently insignificant within the limit of which it would be seriously distorted by a blow, but is quite large in amount where resistance extends to the point of rupture. This is perfectly consonant with that knowledge of the material which every mechanic derives from experience with it. Here, however, we have a complete account of its properties, written out by the material itself with definite and accurate measures.

11. General Conclusions.—These plates, exhibiting the diagrams, which are the autographs of all the useful metals, illustrate sufficiently well the remarkable fullness and accuracy with which their properties may be graphically represented, and the convenience with which they may be studied, with the aid of so simple a recording machine. A comparison of results deduced as shown, with those obtained, so far as they can be obtained at all, the usual method of simply pulling the specimens asunder, and trusting to, sometimes, unskillful hands and an untrained observer, for the adjustment of weights and the registry of results, will indicate the close approximation of this method in even ascertaining the behavior of the metal in tension. On examining the beautifully plotted curves given by Knut Styffe, as representing the results of the experiments, made by him and by his colleagues, with a tensile machine, no one can fail to be struck with the similarity of those diagrams to the curves here produced automatically, and it will be readily believed that not only must there be very perfect correspondence of results where the two methods are carefully compared, but, also, that any theory of rupture must be defective which does not apply to both cases. The equations of the curves here given and those of the curves obtained by Styffe must have forms as similar as the curves themselves.

The constant ratio here assumed between the torsional resistance and the tensile strength of the metals, and of homogeneous materials generally, is based upon a comparison of the results here given with

those obtained from the irons by tensile test, by the writer, and is confirmed by a compilation of results given by other experiments on the same brands.

12. Testing within the limit of Elasticity.—In determining the value of materials of construction, it is usually more necessary to determine the position of the limit of elasticity and the behavior of the metal within that limit than to ascertain ultimate strength or, except, perhaps, for machinery, even the resilience. It is becoming well recognized by engineers who are known to stand highest in the profession, that it should be possible to test every piece of material which goes into an important structure and *to then use it* with confidence that it has been absolutely proven to be capable of carrying its load with a sufficient and known margin of safety. It has quite recently become a common practice to test rods to a limit of strain determined by specification, and to compel their rejection when found to take a considerable permanent set under that strain. The method here described allows of this practice with perfect safety. The limit of elasticity occurs within the first two or three degrees, and, as seen, the specimen may be twisted a hundred, or even sometimes two hundred times as far without even reaching its maximum of resistance, and often far more than this before actual fracture commences. It is perfectly safe, therefore, to test, for example, a bridge rod up to the elastic limit, and then to place the rod in the structure, with a certainty that its capacity for bearing strain without injury has been determined and that formerly existing internal strain has been relieved. The autographic record of the test would be filed away, and could, at any time, be produced in court and submitted as evidence—like the "indicator card" of a steam engine—should any question arise as to the liability of the builder for any subsequent accident, or as to the good faith displayed in fulfilling the terms of his contract. A special machine has been designed for this case.

13. The above will be sufficient to show the use and the value of this method. In the course of experiment upon a large number of specimens of all kinds of useful metals and of alloys, a number of interesting and instructive researches have been pursued, and some unexpected discoveries have been made. Before taking up the theory of rupture, the construction of equations, and the determination of their constants, a section will be devoted to an account of these investigations.

ON THE MECHANICAL PROPERTIES OF MATERIALS OF CONSTRUCTION,

And on Various Previously Unobserved Phenomena, Noticed during Experimental Researches with a New Testing Machine, with Autographic Registry.

By Prof. R. H. Thurston.

Section II.

SOLUTION OF PROBLEMS AND EXPERIMENTAL RESEARCHES.

14. Introductory.—The preceding section has been devoted to a description of the peculiar form of testing machine employed by the writer during these researches, to an account of the general method of obtaining from any material an autographic record of its mechanical properties, and to the interpretation of strain diagrams thus obtained from the useful metals, and other materials of construction.

The part here presented contains an account of some of the more interesting and fruitful of the special investigations conducted with the apparatus, and embodies a description of certain remarkable and hitherto unobserved phenomena accompanying the distortion of metals, the discovery of which must affect the theory of the effect of stress in producing strain, and consequently will somewhat modify engineering practice.

15. General Deductions.—From what has already been shown, we may deduce the following *résumé* of methods of determining the several more important properties of materials by an inspection of their strain diagrams.

(1). *To Determine the Homogeneousness of the Material.*—Examine the form of the initial portion of the diagram between the starting point and the sudden change of direction which has been shown to indicate the elastic limit. Notice, also, its inclination from the vertical, and compare with it the inclination of the "elasticity line."

A perfectly straight line beneath the elastic limit, perfectly parallel with the "elasticity line," shows the material to be *homogeneous as to strain, i. e.*, to be free from internal strains, such as are produced by irregular and rapid cooling, or by working too cold. Any variation from this line indicates the existence and measures the amount of strain. A line considerably curved, as in No. 6, Plate 1, exhibits the existence of such strain.

Next, examine the form of the curve immediately after passing the elastic limit.

A line rising from the elastic limit regularly and smoothly, approximately parabolic in form, and concave toward the base line, as in No. 22, indicates *homogeneousness in structure*, and the absence of such imperfections as are produced in wrought iron by cinder, or in cast metals, which have been worked from ingots, by porosity of the ingot.

A line turning the corner sharply, when passing the elastic limit, and then running nearly or quite horizontal, as in other irons and in the low steel of Plates II and III, or actually becoming convex toward the base line, as with some of the woods in Plate I; and then, after a time, resuming upward movement by taking its proper parabolic path, indicates a decided want of this kind of homogeneity. The relative length of the depressed portion of the line, and the amount of depression, measures the relative defectiveness of materials compared in this respect. Finally, compare the diagrams produced by several specimens of the same kind of material, or from the same mass.

Homogeneousness in general character and *homogeneousness in composition* are proven by the precise similarity of these diagrams, while a greater or less variation of the curves compared, indicates a greater or less difference in the specimens of which they are the autographs.

Materials should usually exhibit great homogeneousness in all these three ways, to be perfectly reliable. *Perfect* homogeneousness is not to be expected in either respect.

(2). *To Determine the Elastic Resistance of the Specimen.*—Measure the height of the curve at the elastic limit, using the scale of torsion, or for tension, which is given for each machine and for each standard size of test piece, as shown in the accompanying plates.

(3). *To Determine the Resistance Offered to any Given Amount of Extension, or that Producing a Given Set.*—Measure the ordinate of the curve at the point whose abscissa, or distance from the origin, measures the assumed degree of set.

(4). *To Determine the Ultimate Resistance of the Material.*—Measure, in a similar manner, the maximum ordinate of the curve.

(5). *To Determine the Resilience of the Piece Within the Elastic Limit; i. e.*, the work required to produce an evident and permanent set, approximately proportional, in amount, to the degree of change of form of the specimen. This quantity measures the power of the material to resist blows, and its determination is evidently quite as important as that of resistance to static stress, which latter forms one of the factors of the former.

Measure the area comprised between the ordinate of the curve at the elastic limit and the initial part of the curve. This quantity is proportional to the required value. *Or*, multiply the elastic resistance of the material by the extension within the elastic limit. As an approximate result, two-thirds this product is the quantity required, in inch-pounds or foot-pounds, according as measures of extension are taken in inches or feet.

(6). *To Determine the Resilience of the Material Within any Assumed Limit of Extension, i. e.*, the magnitude of blow required to produce a given set.

Measure the area of the curve up to the assumed limit; as, for example, the area, in Plate III, under No. 21, Z, 21, 21, Y, x; where the assumed set is the extension from Z to x. Two-thirds the product of the resistance, measured by the altitude $Y\,x$, and the extension $b\,x$, gives, as before, an approximate value for ordinary purposes.

(7). *To Determine the Total Resilience,* or shock-resisting power, of the material. Measure the total area of the diagram. For ductile materials, an approximate value is obtained by taking two-thirds the product of the maximum tenacity by the maximum extension. For hard and very brittle materials, one-half the same product gives very accurately its values. For intermediate qualities, the true value is more nearly two-thirds this product, also. Swedish wrought-iron, white cast-iron, and hardened steel illustrate the first and the second classes; ordinary tool steels are examples of the third class, as is also iron like No. 22.

(8). *To Determine the Effect of a Load Given in Pounds per Square Inch of Stress.*—Find a point in the curve having an ordinate which measures the given stress. The abscissa of that point measures the extension under that load. In other words, a point being found in the curve, the height of which above the base line is equal to the load per square inch, its distance from the origin measures the extension of the material as produced by that stress.

(9). *To Determine the Effect of a Blow, or a Shock, whose Measure is given in inch-pounds of Energy, i.e.*, of which the work, which it is capable of doing, is known.

Find a point on the curve whose ordinate cuts off an area, between itself and the origin, representing the given amount of work. Or, find such a point that two-thirds the product of the stress measured

by its ordinate, and the extension corresponding to its abscissa, is equal to the number of inch-pounds given. The position of this point shows the maximum strain and the maximum extension of the material under the assumed conditions.

Drawing a line through this point parallel to the nearest "elasticity line," the distance of the point at which it intersects the base line from the origin indicates the resulting set.

(10). *To Determine the Effect of a Blow upon the Material when already Strained by a Dead Load.*—Determine first the extension produced by the application of the static stress, as in (8), and then find that point on the curve between the ordinate of which and the ordinate of the point indicating the strain just found as due the dead load, an area is intercepted which measures the work done by, or the energy of, the shock which has been assumed or calculated.

16. Examples.—Illustrations of the first seven of the above de scribed processes are given either in the preceding portions of this paper, or will be noticed hereafter during the progress of special searches. Those succeeding may be illustrated thus:

(1). Given, a load of 30,000 pounds per square inch. Determine its effect upon good qualities of cast and wrought iron, low steels, tool steel and the weaker metals.

Referring to plate II for examples, we find that neither cast copper, lead, tin, nor zinc would sustain such strain. All would be broken.

Good iron, Nos. 1 and 6, would be strained beyond their limit of elasticity and would take a set after an extension of about 1 and $1\frac{1}{2}$ per cent. respectively. The exceptional iron, No. 22, would be strained to a point which is so nearly its elastic limit that it would remain practically uninjured.

The low steels, Nos. 69, 67, 76, would bear the stress with a similar degree of safety, very nearly. The first would have a considerable margin of safety within its elastic limit; 67 would be nearly, and 76 would be quite, strained to the elastic limit, while 98 would take a set of about one-fifth of one per cent.

If the strain were torsional, the weaker metals would be twisted off by a force corresponding to that here assumed, the good irons would take a set of about 25°, the best iron and the three stronger steels would take no appreciable set, and the softest of the latter would set at about 10°. In these cases, the specimens are supposed of standard

size. For other sizes the forces producing similar effects would vary as the cube of the diameters.

(2.) Given, the magnitude of a shock, or blow, *e. g.*, as equal to that due a weight of one ton,—2000 pounds,—falling one foot, the rod taking the strain being of one square inch area of section, and one foot long. Determine the effect for each of the above-named materials.

The effect of this blow is equivalent to an expenditure of energy amounting to $2000 \times 12 = 24000$ inch-pounds.

The weaker materials, not possessing an ultimate resilience of this amount, would be broken.

Forged copper would be strained, and would take a set after very nearly 12·5 per ct. of extension, since $0{\cdot}125 \times 12 \times \frac{24000 \times 2}{3} = 24000$, the work done by the blow being equilibrated by the product of two-thirds the resistance, noted at 110°, Plate II,—$\frac{24{,}000 \times 2}{3}$,—into the extension $0{\cdot}12\frac{1}{2} \times 12$ inches. Perfect accuracy of figures may be insured by perfectly accurate measurements.

The specimen of iron No. 1 would be given an extension and set of very nearly 0·068, since the resistances under this amount of stretch would be approximately 45,000 pounds per square inch, and the work during extension would be $0{\cdot}068 \times 12 \times \frac{45{,}000 \times 2}{3} = 24{,}000$ inch-pounds.

The iron of special grade No. 22 would be elongated 0·058=0·69 inch,—as $0{\cdot}069 \times 12 \times \frac{52{,}000 \times 2}{3} = 24{,}000$ nearly.

The same blow would produce on the rod, if made of such steel as No. 69, an extension of $0{\cdot}0384 \times 12 = 0{\cdot}461$ inch, estimated thus,—$x = 24{,}000 \div \frac{2}{3} \cdot 78{,}000 = 0{\cdot}461$, it being found, by "trial and error," that the extension 0·0384 develops a maximum resistance of 78,500 pounds per square inch.

It is evident that where extreme accuracy is required the curves should be transferred to a new scale, in which the abscissas should be a scale of elongation instead of angular distortion, and the area should be carefully measured.* For the latter work an Amsler "Planimeter"† is useful.

* See London "Engineer," Nov. 8th, 1872.

† It is evident that diagrams accurately representing tests made with the common testing machine afford similar facilities for solving these problems.

(3.) Given, a bolt of dimensions as last assumed, strained with the effect of a load of 30,000 pounds, as in example (1). Determine the effect of a blow of 24,000 inch-pounds energy, occurring while the bar is sustaining the static load.

The effect of the dead load, as already calculated, is to produce a strain upon the low steels, and upon iron like No. 22, which would keep them extended only a very minute fraction of their original length, this extension being, even with the latter material, but 0·05 of one per cent.

The effect of the blow would be, practically, the same as has just been estimated for the unloaded bar.

Nos. 1 and 6 would be, as already shown, extended one and one and a half per cent., respectively, by the simple load. The added effect of the blow would be to produce an additional extension and set of 0·0533 and 0·0555 respectively, since the mean resistance, during this extension, is $\frac{45,000+30,000}{2}$ and $\frac{42,000+30,000}{2}$, respectively, and the extension must be, $24,000 \div \frac{45,000+30,000}{2} \div 12 = 0{\cdot}0533$, and $24,000 \div \frac{42,000+30,000}{2} \div 12 = 0{\cdot}0555$.

The bar is stretched, in the first case, 0·64 inch; in the second, 0·666 inch, by the blow, if made of such iron as that of specimens 1 and 6.

It should be remarked here, that although the diagrams obtained from the various materials tested give data from which to estimate their relative value in resisting shock, the absolute results of calculation, with no modification for varying rapidity of action, will be but approximate.

This is a consequence of the facts that the inertia of the body struck will affect the result, and that the actual resistance varies with the velocity of rupture. A rod which will sustain safely the blow of a heavy body, would yield readily under a blow of similar energy struck by a light weight moving with proportionally increased velocity. The mathematical investigation of this effect, which has not hitherto been noticed, remains to be given. It is only necessary to state here that a rod of uniform section, and homogeneous in structure, will be uniformly extended by a force slowly applied. A blow received at one end will extend it most at the portion nearest that end, and the more rapid the blow the more is its effect concentrated. It is possi-

ble to produce actual fracture at one end by a very rapid blow, and for rupture to become complete before the shock is felt at the opposite end. This action is seen daily in every workshop where pieces are broken from heavy masses by the blow of a hammer.

The effect of a blow depends, therefore, not only on the magnitude of that product of mass into height due its velocity which we call *vis viva*, but also upon the magnitude of the factors. It further follows that, of two materials having equal tenacity and equal ductility, that having the greatest density will be most liable to fracture by impact.* This information is confirmed by experience.

In general a rod should be somewhat larger at the end receiving the shock, and this enlargement should be greater as the blow is more rapid. Conversely, blows of equal energy are most injurious when given by bodies of light weight moving at high speed. This difference is exaggerated by any cause which increases the density of the material. The variation of resistance with rapidity of rupture will be considered more at length hereafter.

It is readily seen that we have here an explanation of the fact, that fracture produced by a quick blow is granular in character, while a steady pull brings out the "fibrous" texture of iron. In the former case the action is concentrated upon a cross-section close to the point at which the blow is received; in the latter instance inertia acts less effectively in resisting the transmission of the rupturing force to other portions of the piece, and the drawing out process is permitted to take place.

17. Peculiar Problems sometimes present themselves in practice which cannot be solved by any published methods—why, it is difficult to say, but partly, it is probable, because of a deficiency of experimental data, and partly because known authorities have not been led by actual experience in engineering practice to perceive the importance of their applications.

Of these the following is an example:

To determine the effect of a succession of stresses, whether static or dynamic, each of which strains the material beyond the original or the acquired limit of elasticity. An illustration of this action is given by the repeated bending, stretching, or other form of distortion by external force, of any material producing at each application a new set. The same case is illustrated by the gradual elongation of a rod

* "Mechanics' Magazine," Dec., 1871, p. 492.

by repeated blows, the energy of each of which exceeds the elastic resilience of the material.

Determine the elastic resilience of the material existing previous to the application of each stress, by taking the area comprised between two lines drawn through that point on the curve of the material chosen, whose abscissa represents the existing extension, one of which lines is an ordinate and the other of which is parallel to the nearest "elasticity line." This area represents the elastic resilience of the piece; *i. e.*, a blow having an equivalent energy would leave the piece uninjured and without set. Deducting this amount from the energy of the given blow, the remainder of the work done by that blow is expended in producing set or extension, and may be determined as already described.

The effect of a simple force may be determined by deducting from the total distortion produced by each application of that force, the elastic range of the material.

It is thus readily ascertained, in either case, how much each application will add to the set, and how many applications will be required to produce rupture.

It is here assumed that distortion within the elastic limit leaves the piece uninjured, however often it may be repeated. This assumption seems correct, *a priori*, and is well sustained by the valuable researches of Wohler* and others.†

The effect of repeated bending or other form of strain, can thus be inferred from an examination of the strain diagram of the material, obtaining from a single experiment a determination hitherto only obtained by a long and tedious process of repeated distortion. Such investigations of the "fatigue" of metals are often of great importance.

18. The Effect of Time on Metals left under Strain.—The effect of stress is modified when metals are left under strain for considerable intervals of time. It had generally been supposed that this effect was to weaken the resistance whenever the material was left exposed to a strain exceeding the elastic limit.

This idea seems sustained by the experiment of M. Vicat, made at Paris about forty years ago.‡

* *Zeitschrift fur Bauwesen*, 1860; *Festigheitversuche mit Eisen und Stahl*, Berlin; also Lond. *Engineering*, 1871.

† Fairbairn: *Civil Engineer and Architects' Journal*, Vols. XXIII, XXIV.

‡ *Annales de Chimie et de Physique*, 1834, Tome 54, p. 35.

M. Vicat states that four wires were extended, respectively, by $\frac{1}{4}$, $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{3}{4}$ their ultimate resistance, and their elongations were observed and recorded at intervals of one year.

The relative extensions observed indicated a gradual lengthening of the three which were strained beyond the elastic limit, and that most strained finally broke, after sustaining $\frac{3}{4}$ its original ultimate breaking weight two years and nine months, the point of rupture being finally determined by the action of corrosion which had not been entirely prevented.

The several extensions were as follows :

No. 1,	sustaining	$\frac{1}{4}$,	33 months,	. . .	0·000 per cent.
No. 2,	"	$\frac{1}{3}$,	" "	. . . .	0·275 "
No. 3,	"	$\frac{1}{2}$,	" "	. . .	0·409 "
No. 4,	"	$\frac{3}{4}$,	" "	. . . .	0·613 "

The rate of extension was nearly proportional to the times, and the total extension to the forces. M. Vicat concludes that metal thus overstrained will ultimately break, and his paper has caused much uneasiness among members of the profession, as indicating a possibility of the ultimate failure of structures having originally an ample factor of safety.

The elegant and valuable researches, also, of H. Tresca, on the flow of solids,* and the illustrations of this action almost daily noticed by every engineer, seem to lend conformation to the supposition of Vicat.

The experimental researches of Prof. Joseph Henry, on the viscosity of materials, and which proved the possibility of the coexistence of strong cohesive forces with great fluidity,† long ago proved, also, the possibility of a behavior in solids, under the action of great force, analogous to that noted in more fluid substances.

On the other hand, the researches of the writer, as described in the first section of this paper, indicating, by the form of strain diagrams, that the progress of this flow was accompanied by increasing resistance, and the corroboratory evidence furnished by all carefully made experiments on tensile resistance, as those of King and Rodman, Kirkaldy and Styffe, made it appear extremely doubtful whether materials were really weakened by a continuance of any stress, not originally capable of producing incipient rupture.

* *Sur l'Ecoulement des corps solides*, Paris, 1869–72.

† *Proc. Am. Phil. Society*, 1844.

18. To determine this point, a series of experiments was made, the general result of which was first formally announced in a note to the American Society of Civil Engineers,† in which the first experiment, commenced during the session of the National Academy of Science at the Stevens Institute of Technology, was described, and in which the first deductions, since slightly modified by an extended investigation, were given. In Plate III, No. 16, is a *fac simile* of the strain diagram obtained at the first experiment.

A piece of iron, of a good quality of metal, but badly worked, as shown in the sketch already given in Section 1, was placed in the machine and strained considerably beyond its elastic limit. It was then left twenty-four hours under the strain thus produced at A, Plate III. At the end of this period, the pencil was found precisely as it was left, and not the slightest evidence of yielding was noted. The slight depression observed in many examples to be given, is produced by a slight compression of the wood used in blocking the machine at the beginning of the interval. No evidence of flow was therefore obtained.

Upon attempting to produce further change of form, however, the unexpected discovery was made that the test-piece had acquired an increased resisting power. The pencil, instead of following the general direction taken the day previous, rose, as seen in the diagram, until a resistance was indicated, *exceeding by nearly thirty per cent.* that shown before the specimen was left under strain. This resistance having been overcome, the piece yielded with a slightly decreasing resistance, and, after considerable additional distortion, was left at B twenty-four hours. The result of the second experiment is seen to be an increase of nearly fifteen per cent., and a third trial at C gave a small, but still perceptible, gain also.

This singular phenomenon appeared so remarkable and so important that experiments were continued upon various grades of iron, and upon other metals, the greatest care being taken to avoid any possible source of error. Several strain diagrams are given illustrating some of these experiments.

No. 10 represents that of a piece of good iron which is far more homogeneous and better worked than 16.

No. 68 is a piece of "Siemens-Martin steel" which was left under

† *See Trans. Am. Soc. C. E.*, Nov. 1873; *Journal Franklin Institute*, March, 1874.

strain, at *A*, twenty-four hours, and at *B* an equal length of time. In the latter case, the applied force was wholly removed, at the end of twenty-four hours, before an attempt was made to produce further change of form. On renewing the strain the resistance is seen to have acquired an increased intensity very nearly absolutely equal to that shown at *A*, and relatively greater, a fact which will be found to aid in the determination of the real character of the phenomenon. A third experiment, at *C*, shows a repetition of this action, and a fourth, similar to that at *B*, in all except time—for in the last experiment the time was but a fraction of an hour—gave a similar result. In each case it is noticeable that a slight fall from the maximum attained follows the yielding of the test-piece.

No. 33, malleable cast iron, No. 52, double shear steel, and No. 81, tool steel, all exhibit this same stiffening under prolonged strain.

No. 17, "homogeneous chrome iron," was subjected to experiment four times. At *A*, the effect is very marked, and the resistance to further change of shape continues to increase slowly until left at *B* for a second trial. The maximum attained at *B* is not sustained, as further distortion occurs, and, after a slight decrease, the specimen was again left, the pencil resting at *C*.

Next day, the increase of resistance was found less considerable than at the previous experiment, and the line, after passing a maximum a few degrees beyond, falls quite rapidly. Fearing that the metal was about to rupture completely, it was left once more at *D*, another day, after which time its behavior was similar to that on earlier trials. It fully regains the maximum power of resistance noted after the trial at *C*, and, before rupture, it even slightly exceeds it.

The hardest material experimented upon was the very hard chrome steel, No. 21. Left at *A* three days, the resistance at that degree of distortion was increased about eight per cent., and, again at *B*, four days under strain gave a rise of nearly four per cent., after which a considerable rise occurred, in the ordinary manner, before rupture took place.

An interesting experiment was made with the best Swedish iron, a metal of such wonderful purity and ductility that one specimen, of standard size. was twisted nearly 600° before completely breaking off.

No. 101, Plate III, is the strain diagram of the specimen tested for the purpose of determining the effect of continued stress. Here,

as seems frequently the case, a loss of ductility apparently accompanies the increase of resistance. and the total resilience appears to be comparatively slightly altered.

This specimen was strained until the limit of elasticity was just passed and was then left at *A* one day. The result, with even this slight distortion of but six degrees, producing an extension of a very minute amount, is similar to that before noticed, and the behavior here exhibited probably gives a clue to the causes of this peculiar action. After this trial several others were made, and the metal is seen to have behaved in a manner precisely similar to the other grades of iron.

20. Reviewing all of the large number of experiments made since the discovery of this effect of continued strain, carefully comparing the curves obtained with each other, and with the diagrams obtained in the ordinary way, and, finally, making a comparison of the conclusions drawn from this research, with the results of the experimental work of other investigators, the writer has been led to the following, as the most probable explanation of this singular molecular phenomenon.

These strain diagrams are the *loci* of the successive limits of elasticity of metal, at successive positions of set.

The phenomenon here discovered is an elevation of the limit of elasticity by a continued strain. The cause is probably a gradual release of internal strain, occurring in a somewhat similar manner to that observed previously in cast iron in large masses, and, less frequently, and generally in a less marked degree, in wrought iron and other metals, which have been worked in large pieces, and in which such strain has been more or less reduced by a period of rest.*

This loss of strength in large masses of wrought iron is stated, by Mallet, to amount frequently to one-half.†

21. The manner in which this reduction of internal strain occurs, by continued stress at the limit of elasticity, as here observed, may be readily conceived.

When the metal is thus strained, many sets of molecules are placed in positions in which they exert a maximum effect tending to produce

* Compare London "Iron," Stability of Iron Structures, Feb., 1874; Van Nostrand's Magazine, April, 1874.

† On the co efficients of elasticity and rupture in wrought iron in relation to the volume of the mass, its metallurgic treatment and the axial direction of the constituent crystals. *Proc. Inst., C. E.*

molecular changes which may equalize the originally irregular distribution of inter-molecular stresses. After a time, the change actually takes place by "flow," and the resisting power of the piece becomes increased, and its limit of elasticity raised, simply because its forces are now no longer divided, and may act together in resisting external forces. The diagram itself exhibits the best evidence of the occurrence of flow, but it is also shown by an inspection of the broken specimen, as in Figures 6, 7 and 11, of Section I.

It was at first suspected that an action had been detected in this phenomenon, similar to that by which the "portative force" of a magnet is increased by loading its keeper more and more heavily until it becomes "supersaturated." It is not impossible, perhaps not improbable, that the two cases are similar, in some respects, this behaviour of the cohesive force in the present example, aiding to produce the extraordinary increase of resisting power here observed.

A comparison of the ductility registered by samples variously treated lends some confirmation to the supposition, formerly expressed, that, in all cases, the resilience does not increase in the same proportion as the increase of mean resistance, as a consequence of sustained stress, and this, if a fact, may possibly be considered as corroborating the idea just suggested.*

The discovery of this elevation of the elastic limit in all metals examined is also probably confirmatory of this idea.

If the explanation, just offered, of the apparent strengthening action of prolonged stress is correct, the conclusions of Vicat are not overthrown, although evidently not fully justified by his own experiments,

*Since the above was written, the *Journal of the Franklin Institute* has, in the issue for March, 1874, given an account of experiments made by Com'd'r Beardslee, U. S. N., during which metal strained beyond the elastic limit by tension, exhibited a gain of resistance at a position of earliest set, *i. e.*, an elevation of the elastic limit, from 23,075, to 26,100 pounds per square inch, 13.1 per cent., in seventeen hours. The material was bloom iron turned approximately to one half square inch section.

A very important fact noted by the experimenter is that an apparent positive action was observed in the metal under strain by which the scale beam was actually thrown up by a force measuring 125 pounds. If this observation is not erroneous, or, if the action was not due to some accidental circumstance, we may have here a measure of the *intensifying effect* above described.

Commander Beardslee has communicated to the writer the experimental confirmation of the fact, deducible from the explanation here given, that this release of internal strain occurs to a nearly equal extent if the strained piece is simply laid aside for a similar interval after it has been given a set.

and although the intervening forty years of engineering practice have not produced evidence which may be considered as confirmatory of them.

The same molecular movement, or flow, which rearranges the internal forces and relieves internal strain, may be a phase of that viscosity which Vicat supposed might in time permit rupture of metal, subjected to stress nearly approaching its original ultimate resistance, the one action being a more immediate result than the other, and the latter producing its effect, even when cohesive force may have been actually intensified.

Should this prove to be the fact, it would seem allowable to conclude that the forces of polarity and cohesion are not identical. The cause of the apparent increase of strength of iron, with increase of temperature, is seen to be explained by this relief of internal strain, which occurs most readily at high temperatures.

The experiments of the writer have not indicated the possibility of continued flow, and, consequently of ultimate rupture, except under stress, increasing in intensity up to the full maximum resistance of the material.* They do not, therefore, confirm Vicat's deductions, and the inference would seem, on the contrary, to be—that structures of metal do not become weakened with age, except as injury occurs by corrosion, or by overloading. The experiments of Roebling† and his opinion, as expressed in his report on the Niagara Suspension Bridge, are apparently correct.

Kirkaldy, also, concludes that the additional time occupied in testing certain specimens of which he determined the elongation "had no injurious effect in lessening the amount of breaking strain."‡ An examination of his tables shows those bars which were longest under strain to have had highest average resistance.

22. Wertheim supposed that greater resistance was offered to rapidly, than to slowly, produced rupture; Kirkaldy concludes that the contrary is the case. Redtenbacher§ and Weisbach|| assume the law of resistance to be the same beyond the limit of elasticity as within it, and deduce formulas for resistance to shock which are widely inaccurate.

* Compare Kirkaldy—*Experiments on Wrought Iron and Steel*—pp. 62–69; also see the plates given by Styffe, exhibiting curves for tension.

† *Journal Franklin Institute*, 1860; Vol. XL, p. 360.

‡ *Experiments on Wrought Iron and Steel*, pp. 62, 83.

§ *Der Maschinenbau*, Vol. 1. || *Mechanics of Engineering, etc.*

The experiments of the writer prove that, as had already been indicated by Kirkaldy (whose results, however, had been looked on by many of the profession with some suspicion), a lower resistance is offered as the stress is more rapidly applied. This conspires with *vis viva* to produce rupture.

This is seen at *w*, No. 101, Plate III, where a sudden increase of velocity produced a depression of the line, at the angle 110°, and it is exhibited in a much more marked degree in No. 118.

In the latter example, the strain was gradually applied until the point *a* was reached, when, with a suddenly applied force, a motion estimated at about one-tenth of a foot per second, was obtained and, immediately at *b*, the resistance fell off very considerably, the pencil dropping to *c*. Again resuming the slowest movement, about one hundredth of a foot or less per second, resistance rose again to *d*. A repetition of the rapid movement between *d* and b^1, was followed by a loss of resistance again from b^1 to c^1, and, as is seen by the diagram, this occurred whenever the experiment was repeated. At *k*, distortion by a very slow movement was resumed, and continued until the specimen broke. Here we have, probably, the first direct determination of this question, in which the effect of *vis viva* does not appear.

We may, therefore, conclude that the rapidity of action, in cases of shock, and where materials sustain live loads, is a very important element in the determination of their resisting power not only for the reason given already in paragraph 6 of this section, but because *the mnre rapidly the metal is ruptured, the less is its resistance to rupture.* This loss of resistance is about 15 per cent.* in No. 118.

The cause of this action we may presume to bear a close relation to that operating to produce the opposite phenomenon of the elevation of the elastic limit by prolonged stress, and it may probably be simply another illustration of the effect of internal strain.

With a very slow distortion, the "flow" already described occurs, and but a small amount of internal strain may be produced, since, by the action noticed when left at rest, this strain relieves itself as rapidly as produced. A more rapid distortion produces internal strain more rapidly than relief can take place, and the more quickly it occurs, the less thoroughly can it be relieved, and the more is the total resistance of the piece reduced. Evidence confirmatory of this

* Compare Kirkaldy, p. 83. where experiments, which are possibly affected by the action of *vis viva* indicate a very similar effect.

explanation is found in the fact that bodies most homogeneous as to strain exhibited the least of these effects.

It does not seem impossible that, at extremely high velocities, the most ductile substances may exhibit similar behavior, when fractured by shock, or by a suddenly applied force, to substances which are really comparatively brittle.

In the production of this effect, which has been frequently observed in the fracture of iron, although the cause has not been recognized, the inertia of the mass attacked and the actual depreciation of resisting power just observed, conspire to produce results which would seem quite inexplicable, except for the evidently great concentration of energy here referred to which, in consequence of this conspiring of inertia and reduced resistance, brings the total effort upon a comparatively limited portion of the material, producing the short fracture with its granular surfaces, which is the well known characteristic of sudden rupture.

Any cause acting to produce increased density, as reduction of temperature, evidently must intensify this action of suddenly applied stress.

The liability of machinery and structures to injury by shock is thus greatly increased, and it is quite uncertain what is the proper factor of safety to adopt in cases in which the shocks are rapidly produced. This uncertainty must remain until further experiment shall be made the basis of a correct mathematical expression of the natural laws involved in the problem.

Meantime the precautions to be taken by the engineer are: To prevent the occurrence of shock as far as possible, and to use in parts exposed to shock, light and elastic members, composed of the most ductile materials available, giving them such forms as shall distribute the distortion as uniformly and as widely as possible.

23. The behavior of materials subjected to sudden strain is thus seen to be so considerably modified by both internal and external conditions, which are themselves variable in character, that it may still prove quite difficult to obtain mathematical expressions for the laws governing them. It is not improbable, however, that an approximation, of sufficient accuracy for all cases which frequently arise in practice, may be obtained by a study and comparison of experimental results obtained, as above, by the method here adopted, and one which seems peculiarly adapted to the work.

A carefully conducted series of experiments giving quantitative

results would be of great value. Without such a research no reliable knowledge can be obtained of the law of depreciation, and no useful formulas can be devised for use in calculation. The experiments made by the writer are not yet sufficiently numerous or precise to serve as data from which to deduce equations.

24. The Elasticity of the Metals.—The examination of the "elasticity line" will be found to present some facts of interest.

It will be seen that, in every case, the line produced by the descent of the pencil is not precisely coincident with that formed by its rise. This is not due to the friction of the machine, as that would not cause the decided difference observable in the form of the curve. It may be partly due to the fact that the set produced is partly temporary.*

An attempt was made to determine its law by the following method:

A steam gauge having a recording apparatus, in which the paper was moved horizontally, at a uniform rate, by a well-constructed clock, was kindly furnished by the Messrs. Edson, of the New York Recording Gauge Co.

This was set up by the side of the machine, upon a stand on which could be clamped the test piece. The latter carried a light, long pencil holder, so arranged as to traverse the paper in a direction at right angles to that of the motion given it by the clock. An angular motion in the specimen of 0 05° would be readily observed. The specimen was given a degree of torsion of from 10° to 360°, in different cases, and was then rapidly transferred to the stand, where the restoration of form would record itself upon the moving paper, forming a curve of which the ordinates would represent the restoration of form, and the abscissas would be proportional to the time.

In all cases observed, the restoration of form, by loss of temporary set, was so rapid as to have become completed before the specimen could be placed in the recording apparatus, and the record made a straight line invariably.

The conclusion which has finally been deduced from a study of the diagrams obtained is, that the peculiar feature here alluded to is a consequence of an internal molecular friction, the existence of which has already been long suspected by the writer, and probably by many other experimenters.

An illustration of a similar action probably occurs in the behavior of iron under magnetic action. Magnetization produced in bars of

* Morin, *Resistance des Materiaux*, p. 10.

various qualities of iron and steel during important researches of Dr. Joule* and Prof. Tyndall,† proved this behavior to be common to all, when the change of form was produced, within a very minute range even, by magnetic force. Dr. Mayer has more recently‡ examined this peculiar form of molecular action with great skill and thoroughness. Its existence is undoubtedly well proven, and the lines, above referred to, on the strain-diagrams seem to exhibit its effect very clearly. Possibly the rise from *f* to *g*, No. 118, Plate III, is due to such friction.

25. The evident proof found, in the parallelism of all elasticity lines in each diagram, of the fact, first noted by some of the earliest experimenters in this field, that elasticity remains quite unimpaired up to the point at which rupture commences, has been already adverted to.

Coulomb describes a series of curious and instructive experiments which may assist in determining the molecular action occurring in these instances where great distortion and great permanent displacement of particles takes place without loss of elasticity.§

He found this to occur, not only with metal wires, but with threads of fine clay, 1–12 of an inch in diameter and 11 feet long, which could be twisted 5½ turns repeatedly without set and without apparent loss of elasticity. Turning the thread through a wider range of torsion, it always returned but 5½ revolutions, and in each new position of set exhibited the same elasticity as before.

The explanation of this action, as illustrated by the strain diagrams of Plates II and III, and by Coulomb's experiments, is probably also to be found in the phenomenon of flow of solids. The restoration of cohesion, in bodies actually separated, exhibits the extent to which this action may proceed. Two freshly cut surfaces of lead when brought together with a moderate pressure cohere firmly; and plates of glass, laid one upon another, sometimes "seize" each other so firmly that they are cut and worked as one piece.|| The welding of iron is another and a very familiar illustration of the same action. Cohesion may therefore be actually destroyed and renewed, and mole-

* *Philosophical Magazine*, 1874. † *Researches on Diamagnetism*, etc., 1870.

‡ "*Effects of Magnetism in changing dimensions of iron and steel bars*," by A. M. Mayer, Ph. D.; Stevens' Institute of Technology, 1872. *American Journal of Science and Arts*, 1873.

§ *Lecture Notes on Physics*, Mayer; *Journal Franklin Institute*, 1868.

|| *Miller, Chemical Physics*, p. 67.

cules may move among each other, changing completely their relative positions, without loss of either strength or elasticity.

The results of these experiments on metal are important as exhibiting the error of the opinion hitherto entertained by many physicists and engineers, among whom was the writer,† that straining metal might weaken it, even when rupture did not commence, and even where no condition of internal strain was induced. It has been here shown that elasticity remains unimpaired, and resistance continually increases up to the point at which incipient fracture takes place. No well proven exception to this law has been observed.

26. While comparing the inclination of the elasticity lines with the initial line, to determine the pressure and the amount of internal strain, it has been noticed that more or less strain seems almost invariably to exist, but that the amount, as indicated by the difference in inclination of the two lines, is not always as well shown by the greater or less curvature of the initial portion of the diagram. The probable reason would seem to be that this strain is not always uniformly distributed. Were the strain considerable and uniformly distributed, the initial line would be strongly convex toward the base line, and would have the parabolic form. Absence of strain is indicated by a straight line rising regularly to the elastic limit, or, in many cases where the elastic limit is very low, and when the material is inelastic and flows without tendency to recoil, concave toward the base, and parabolic. Irregularly distributed strain would modify the parabolic curve, and the amount of strain would determine the total curvature.

The initial and elasticity lines have, therefore, great interest as revealing important and otherwise unrecognizable properties of the material.

It has been remarked that the difference of inclination just referred to, proves the truth of the assertion of Hodgkinson that every load produces a set. It can now be readily seen why this should usually be the fact, and also that, although it is true, it does not necessarily indicate injury of the material.

Since, in its ordinary state, many sets of particles are usually in a condition of maximum strain, the slightest application of external force to the piece will destroy the existing equilibrium among these conflict-

† *Journal Franklin Institute.*

ing forces within the mass, producing a change of form, and either rupturing or producing a flow of those particles which are most strained, and thus causing a new condition of equilibrium, the piece returning only approximately to the original form when relieved. The greater or less the applied force, the greater or less the number of displaced particles, but it is only when the set becomes nearly proportional to the distortion that it assumes the character in which it is looked upon as a serious effect.

With perfectly homogeneous materials, free from internal strain, no such action would be noticed, and the earliest set would occur beyond the elastic limit, which limit is here considered to be attained when the set becomes proportional to the distortion.

27. The very minute range of distortion within the elastic limit is shown by the strain-diagrams very beautifully. This point is usually reached with the first 5° of torsion, and where internal strain has been eliminated it is frequently found within 2°, the corresponding extension being much less than ·0001.

Captain Rodman, who has made the most delicate determination yet published,* detects a set of 0·000,001,4 after an extension of 0·000, 27 in a specimen of cast-iron, and the elastic limit, as here defined, is reached after an elongation of about 0·0003, the point not being however, very accurately determinable on account of the insensible change of rate, as already observed, in the strain-diagrams of cast-iron.

The immense magnification on the strain-diagrams, obtained with the torsion machine, of the elongation at the commencement of the curve, enables the behavior of the materials within this minute, yet most important, portion of the entire range to be perfectly represented and permits its examination in a most satisfactory manner.

28. The Influence of Variations of Temperature.—The effect upon the mechanical properties of metal of variations of temperature has long been a subject of debate, and one which has not even yet been satisfactorily settled by experiment.

A *priori* it would appear that, in a perfectly homogeneous material, entirely free from internal strain, change of temperature would produce an alteration of strength and of ductility which would both be the reverse, in direction, of the variation of temperature.

The forces acting to produce mechanical changes being, probably,

* *Experiments on Metals for Cannon, etc.* Rodman, pp. 157-167.

cohesive force, on the one hand, resisting external forces tending to produce distortion or rupture, while the force produced by the energy of heat-motion conspires with external force to produce that distortion, and the molecules being, at every instant in equilibrium between the force of cohesion on the one side, and the sum of the other two forces mentioned, on the other, variations of form must ensue with every change in the relative magnitudes of these forces. A change of temperature produced by an increment of heat energy, it would appear, must produce a reduction of cohesion by separation of particles, and the opposite change must cause an increase of cohesion by their approximation. Increase of temperature, by reducing the range of action of cohesion by separating particles, and causing them to approach the limit of reach of cohesive force, would reduce ductility, and the opposite change of temperature would increase extensibility. The effect on resilience, the product of ductility and strength, would evidently be still more marked than the variation of its factors.

The peculiar behavior of zinc, and the often observed brittleness of iron, at low temperatures, have given cause for doubting the truth of the above statement, and until the phenomena accompanying variations in homogeneousness of structure and composition, and the introduction or removal of internal strain, have been very thoroughly investigated, it cannot be anticipated that the subject will become well understood. The character of polarity, that force of which the presence constitutes the distinguishing difference between solids and liquids, remains to be determined, and its determination may be expected to throw important light upon this subject.

Experiments of both physicists and engineers have failed, up to the present time, to give as much, and as precise information as is needed to determine satisfactorily what rules should govern the proportions of structures, whether carrying dead loads or subjected to shocks or blows, at any given temperature below the usual range, or even at the low temperatures to be met during every winter in the latitude of New York.

In a paper recently published* on "Molecular Changes produced by Variations of Temperature," the writer gave the results of a careful investigation of the experimental work previously done, by both philosophers and engineers, in researches bearing upon this important question.

* *Iron Age*, June, 1873; *Van Nostrand's Magazine*, July, 1873; *Jour. Frank. Inst.* 1873; *London Jour.*, Jan., 1874. Also in pamphlet, p. 29. D. Van Nostrand.

29. The conclusions, as there reached, were the following:—

1. That the number and the nature of those molecular forces which determine the physical condition of matter are not yet fully ascertained, but that these forces manifest themselves in, at least, three distinct modes of action, and, as thus exhibited, they are known as repulsion, cohesion, and polarity.

2. That the force of repulsion is, apparently, heat, motion, or some closely related phase of energy. That the force of cohesion bears some resemblance to that of gravitation, but seems not to be identical with the latter, and that the force of molecular polarity, which determines the molecular relations of position, seems to bear some distant relation to that of magnetic polarity.

3. That the law which governs the variations in intensity of these forces with changes of intermolecular distances, is undetermined, and that it has not been expressed by any mathematical formula, except approximately and for a limited range.

4. That the magnitudes of the intermolecular spaces, and consequently, the volume of any mass, are variable with changes in the relative magnitudes of the forces of cohesion and repulsion.

5. That the resistance offered to change of form is determined by the relations in intensity of the forces of polarity and those forces which determine intermolecular distances.

6. That, at the "absolute zero" (— 461·2° Fahr.), cohesion, and consequently the strength of the material has, probably, its maximum value, heat-energy having disappeared.

7. That, at very high temperatures, heat-energy exerts a separating force upon particles, which entirely overcomes the other forces, and matter, assuming the gaseous state, requires the action of extraneous forces to preserve its volume unchanged.

8. That, at intermediate points, matter, in either the solid or the liquid states, exhibits a definite degree of separation of molecules which is determined by the intensity of the repulsion due to heat-motion, a position of equilibrium being assumed, which, with the same substance, is invariable for the same temperature. The application of some kind of force is required to disturb this equilibrium and to produce change of volume. The amount of this force is determined, for any given extent of disturbance, by the maximum value of cohesion for the substance and the quantity of heat which has been required to raise it from the absolute zero of temperature.

The sum of the applied force, and the force consequent upon the presence of heat-motion, must exceed cohesive force to produce dilatation, while this cohesive force, added to externally applied force, must exceed the force of repulsion to produce diminution of volume.

9. That the distinction between the solid and liquid states of matter seems due to the action, in the former, of the force of polarity, which gives stability of form, while, in the latter, this force is extremely feeble, disappearing altogether when the boundary line between the liquid and gaseous states is reached.

That combined stability and elasticity of volume may be produced by the equilibrium of attractive and repulsive forces, but that stability and elasticity of form demand the coexistence of cohesion and polarity.

10. That the general effect of increase or decrease of temperature is, with solid bodies, to decrease or increase their power of resistance to rupture, or to change of form, and their capability of sustaining "dead" loads.

11. That the general effect of change of temperature is to produce change of ductility, and, consequently, change of resilience, or power of resisting shocks and of carrying "live loads." This change is usually opposite in direction and greater in degree than the variation simultaneously occurring in tenacity.

12. That marked exceptions to this general law have been noted, but that it seems invariably the fact that, wherever an exception is observed in the influence upon tenacity, an exception may also be detected in the effect upon resilience. Causes which produce increase of strength seem also to produce a simultaneous decrease of ductility, and *vice versa.*

13. That experiments upon copper, so far as they have been carried, indicate that, (as to tenacity), the general law holds good with that metal.

14. That iron exhibits marked deviations from the law between ordinary temperatures and a point somewhere between 500° and 600° Fahr., the strength increasing between these limits to the extent of about 15 per cent. with good iron. The variation becomes more marked and the results more irregular as the metal is more impure.

15. That above 600° F. and below 70°, the general law holds good for iron, its tenacity increasing with diminishing temperature below the latter point, at the rate of from 0·02 to 0·03 per cent. for each degree Fahrenheit, while its resilience decreases in a higher but not well deter-

mined ratio for good iron, and to the extent of reduction to one-third its ordinary value, or less, at 10° F. when cold-short, and, in the latter case, the set may be less than one-fourth that noted at a temperature of 84° Fahr.

16. That the viscosity, ductility and resilience of metals are determined by identical conditions, and that the fracture of iron at low temperatures, has, accordingly, been found to be characteristic of a brittle material, while at the higher temperatures, it exhibits the appearance peculiar to ductile and somewhat viscous substances. The metal breaks in the first case, with slight permanent set and a short granular fracture, and in the latter with frequently a considerable set and a form of fracture indicating great ductility. The variation in the behavior of iron, as it approaches a welding heat, illustrates the latter condition in the most complete manner.

17. That the precise action of the elements with which iron is liable to be contaminated, and the extent to which they modify its behavior under varying temperature, remain to be fully investigated, but that the presence of phosphorus, and of other substances producing "cold shortness," exaggerates to a great degree, the effects of low temperature in producing loss of toughness and resilience.

18. That the modifications of the general law with other metals than iron and copper, and in the case of alloys, have not been studied, and are entirely unknown.

19. That these conclusions are sustained by experiments of both physicists and engineers.

"The practical result of the whole investigation is that iron and copper, and probably other metals, do not lose their power of sustaining 'dead' loads at low temperatures, but that they do lose to a very serious extent their power of sustaining shocks or of resisting sharp blows, and that the factors of safety in structures, need not to be increased in the former case, where exposure to severe cold is apprehended, but that machinery, rails, and other constructions which are to resist shocks, should have larger factors of safety, and should be most carefully protected, if possible, from extreme temperatures."

30. The conclusions above given were deduced from the physical investigations of Boscovich, Coulomb, Henry, Powell, Cagniard de la Tour, Andrews, Faraday, Wartmann ,Robinson, Gaudin, Thompson, Rankine and others, and from the more purely technical researches of Professors Johnson and Norton, Fairbairn, Kirkaldy, Brockbank, Joule, Spence, Styffe and Sandberg.

An apparent discrepancy of results from which some experiments seemed to indicate weakness, and others strength of metals as a consequence of reduced temperature, was explained by the fact that those which seemed to prove the first conclusion, were cases in which the metal was tested by blows, and those proving the reverse were tests made by steady strain. The deduction (11), made above, that the result of change of temperature, by producing changes of ductility, which were the reverse of those produced in tenacity, and that the same bar might thus exhibit a higher resistance to static stress while less capable of resisting shock, explained the seeming contradiction.

31. It was evident that, to determine satisfactorily the real effect of changes of temperature, it was necessary to obtain a series of experimental determinations of the simultaneous action of such variations upon both strength and resilience. Such experiments could readily be made by the method here pursued, and a considerable number of observations are represented by strain-diagrams on plate III.

In these experiments, the machine and the test pieces were placed in the open air, where, changing in temperature with the atmospheric changes, no error could arise by transfer of heat during the experiments. The machine and specimens submitted to test were always of the same temperature.

The mildness of the past winter has precluded the determination of the behavior of iron at temperatures very far below the freezing point, the lowest reached being 10° Fahr.

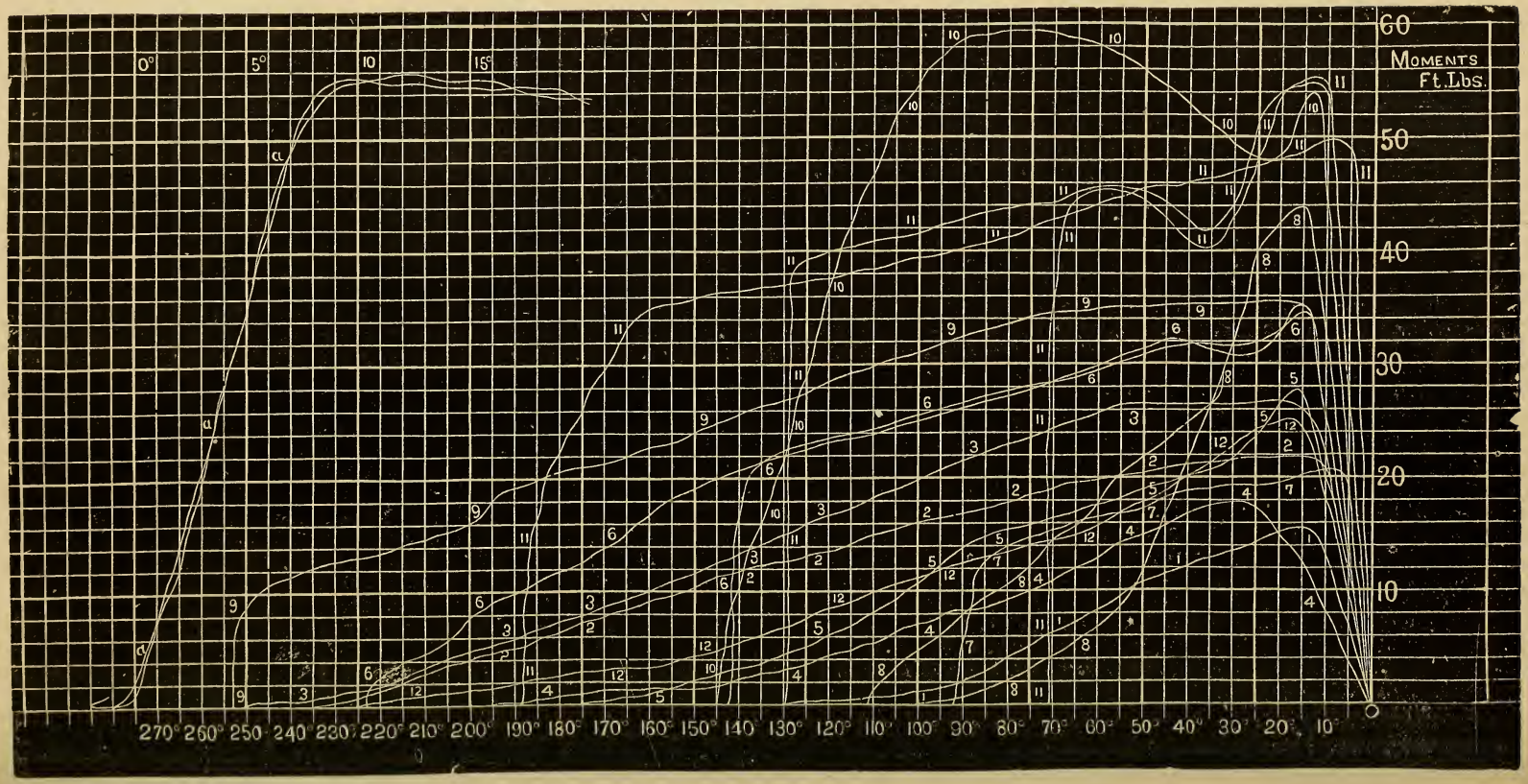
This is the more to be regretted since, as will be seen, there exists a possible change of law near the Fahrenheit zero, and it is extremely important to ascertain whether this indication of an anomaly arises from irregularity in the quality of specimens, nominally of the same grade, or whether it is a real variation of the effect of change of temperature.

As no previously made experiments combine, in the manner here presented, the various effects of heat upon the mechanical properties of the metals, the results obtained are given as a beginning, and the conclusions which are deduced from them are given as merely probable, while it is to be hoped that other members of the profession, who may be so situated that they can readily continue the work at points in the north and north-west where a temperature far below zero is reached, will make more complete and instructive researches during succeeding winters.

AUTOGRAPHIC STRAIN—DIAGRAMS OF WOODS

PRODUCED BY THE

Testing Machine of PROF. R. H. THURSTON.



AUTOGRAPHIC STRAIN-DIAGRAMS OF METALS

PRODUCED BY THE

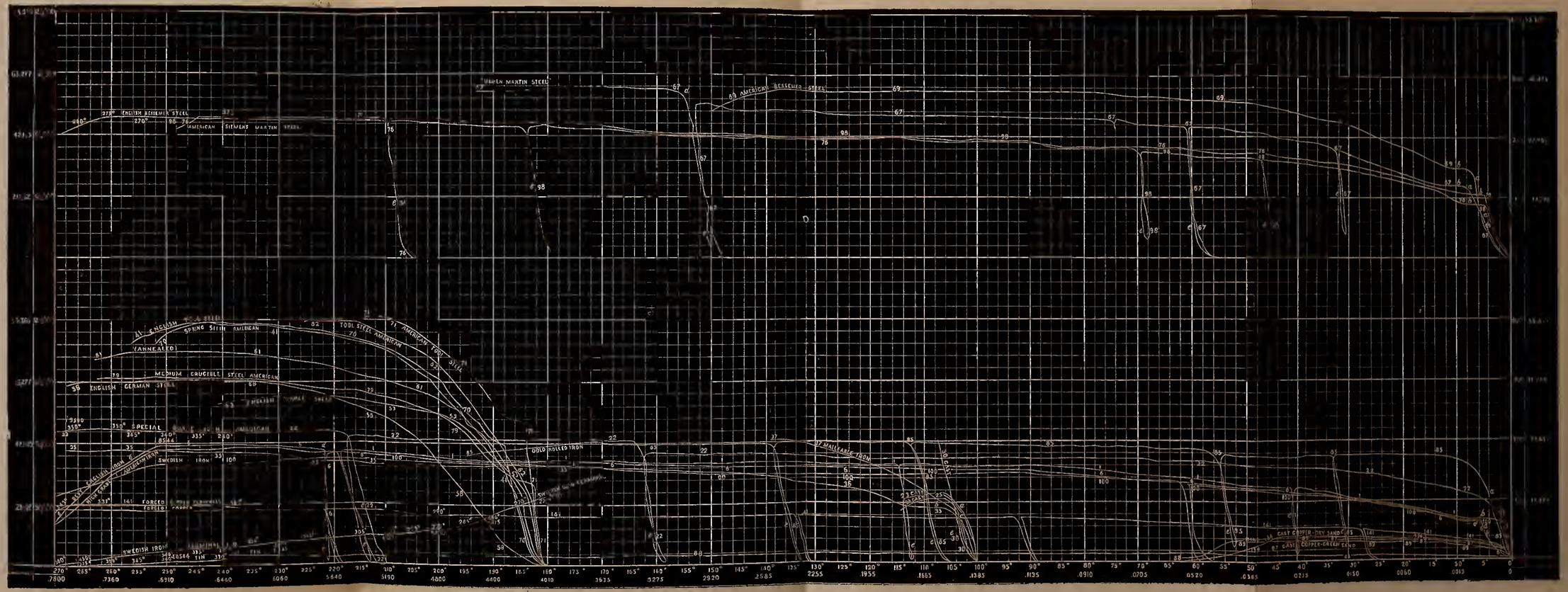
TESTING MACHINE OF PROFESSOR R. H. THURSTON.

Approximate Tensile Resistance.

Kilograms per square Millemetre. | Pounds per square inch of Section.

Torsional Moments.

Foot-Pounds. | Kilogrammetres.



AUTOGRAPHIC STRAIN-DIAGRAMS OF METALS,

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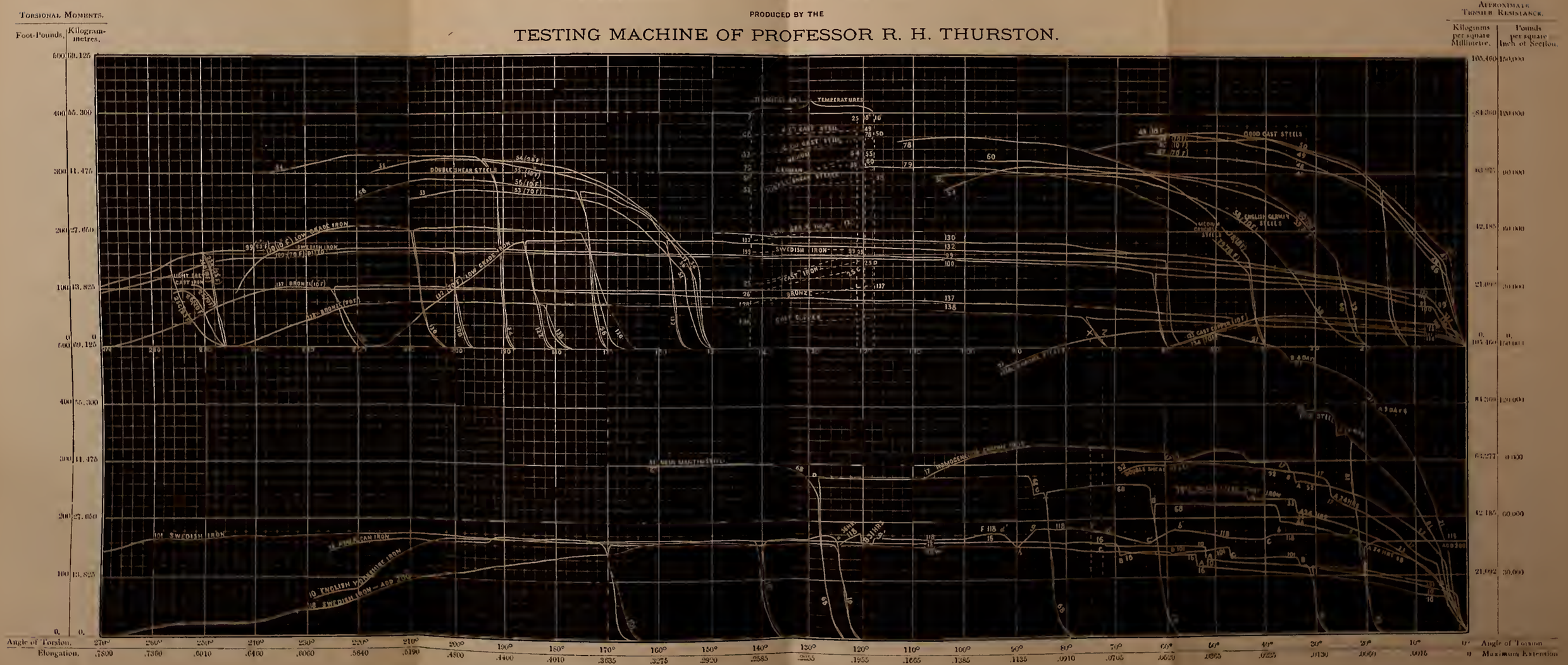

Fig 15.

Fig 16.

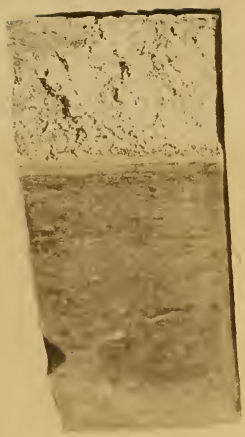

Fig 17.

Fig 18.

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